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Technical Report

No. 13575

INVESTIGATION OF CAST AUSTEMPERED DUCTILE IRON (CADI)

TRACKSHOES IN T-158 CONFIGURATION

CONTRACT NUMBER DAAE07-90-C-R063

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THIS DOCUMENT REPORTS ON THE INVESTIGATION OF CAST AUSTEMPERED DUCTILE IRON (CADI) T-158 TRACKSHOES TO DETERMINE ANY WEIGHT OR COST ADVANTAGES WHICH CAN BE GAINED FROM THE CADI PROCESS. ALTHOUGH THE CADI PROCESS CONSIDERABLY IMPROVES THE MECHANICAL PROPERTIES OF DUCTILE IRON, THIS PROCESS DOES NOT RESULT IN A MATERIAL SUITABLE FOR TRACKSHOES. RESULTS OF BLAST, BALLISTIC, AND COLD TEMPERATURE TESTING DEMONSTRATE THE SUPERIORITY OF FORGED STEEL TRACKSHOES. ANY PROCUREMENT COST SAVINGS ARE OVERSHADOWED BY LIFE CYCLE COST INCREASES FOR A CADI TRACK BASED UPON THEIR REDUCED DURABILITY. AS A CRITICAL SAFETY ITEM, TRACKSHOES REQUIRE GREATER DUCTILITY AND TOUGHNESS THAN IS AFFORDED BY CADI MATERIAL. THIS REPORT RECOMMENDS THAT CADI TRACKSHOES BE REJECTED.

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EXECUTIVE SUMMARY

This report details the work performed by FMC Corporation in the execution of the Scope of Work under Contract DAAE07-90-C-R063.

The objective of this contract was to reduce the weight and costs of T-158 track hardware through the use of Cast Austempered Ductile Iron (CADI), while not degrading the performance relative to the forged trackshoe. Equality of performance was defined for the purpose of this effort as equality in load carrying capability as measured by tensile testing, equality in impact performance as measured by both component and charpy tests, equality in fatigue life by component testing, and equality in resistance to blast and shrapnel by ballistic evaluation.

An initial design review of the CADI trackshoe resulted in several recommended dimensional modifications from the currently used forging (Appendix I). Material was added in highly stressed areas of the trackshoe to optimize the design of the CADI configuration. This was necessary (and approved by TACOM) in an effort to maintain the equality of performance of the CADI trackshoe to the current T-158 track. In low stressed areas, material was removed from the CADI

trackshoe, with the overall result being a 2.6 percent weight reduction of the M1A1 track weight as compared with the T-158 trackshoe. Note, however, that even more of this material has already been removed from the forged steel T-158 trackshoe during the T-158LL program, resulting in a 9 percent reduction of the track weight (2.7 pounds per trackshoe). A weight comparison of the T-158, T-158LL and CADI T-158 track is presented in Table III, along with key dimensions to indicate where material was added to the CADI trackshoe in the interests of achieving equivalent performance. In similar fashion, material was reduced in other areas to save weight where it was not needed.

Following the design review, CADI prototype trackshoes were manufactured to existing industry (ASTM) specifications. It should be noted that the ductile iron specification currently in use is less stringent than forged steel specifications, which implies that the inherent variability of ductile iron process controls is cause for concern in the manufacturing environment (Section 5.4). Appendix VII identifies that internationally there is wide variability in the very definition of CADI material.

The CADI trackshoe may be somewhat less expensive in procurement cost than the forged T-158 shoe body, but the life cycle costs would be

much higher. Based upon the data and analysis contained in this report, the cost effectiveness of the CADI process for application to trackshoes is greatly reduced for three reasons: significantly reduced durability; much higher potential for combat mobility kills as a result of shrapnel and mines; and a higher risk to soldier safety of track separations due to low impact tolerance of CADI. These risks increase even more in cold weather operations.

FMC's Corporate Technology Center (CTC) performed most of the evaluations. Side-by-side testing of impact strength cold temperature performance, ballistic performance, mine simulation, and fatigue life (durability) was conducted. In all cases, the forged steel demonstrated superior performance compared to the CADI material.

Of all tests conducted, the mine and ballistic assessment revealed most clearly the increased vulnerability of the CADI track to fracture and separation under mine or shrapnel attack. This factor alone gives grave concern for the use of CADI track for military vehicles, as the minimum result would be a mobility kill under combat conditions.

Other test data in this report infer that the use of CADI would adversely affect the tension/torsion fatigue strength and energy

absorbing ability of the trackshoes, particularly in cold weather conditions. This duplicates results of TACOM's test report #1-VC-087-130-004, dated 5 April, 1977 wherein significantly increased track breakage was witnessed using CADI track in a vehicle test under cold weather conditions in Canada (Appendix V).

Results of this test series along with the unanswered issues relating to wear, corrosion, and quality assurance lead to a recommendation to reject the use of CADI material for track for military vehicles. The adoption of CADI material for the T-158 track or any other combat vehicle track would represent a significant decrease in soldier safety, both off and on the battlefield.

1.0 INTRODUCTION

This final technical report, prepared by Steel Products Division of FMC Corporation for the U.S. Army Tank-Automotive Command under Contract DAAE07-90-C-R063, describes the manufacture and component testing of Cast Austempered Ductile Iron (CADI) T-158 trackshoes.

2.0 OBJECTIVE

The primary goal was to examine the weight and cost benefits of the CADI trackshoe compared to the current T-158 trackshoe for the M1A1 tank, assuming that the performance of the two tracks was the same.

3.0 CONCLUSIONS

Use of the CADI process for T-158 track production would not achieve significant weight savings (if any at all), but may result in some procurement cost savings. On the other hand, the CADI T-158 trackshoe suffers from significantly reduced fatigue life, impact strength, cold temperature performance, and ballistic performance when compared to the forged T-158 trackshoe. These parameters imply

that the M1 tank (or any other combat vehicle) equipped with CADI trackshoes will experience a greater number of mobility kills on the battlefield, an unacceptable decrease in soldier safety under any conditions, and reduced durability (especially under cold weather conditions) when compared to the current T-158 forged trackshoe. Therefore, Cast Austempered Ductile Iron trackshoes do not appear to promise either a weight reduction or life cycle cost savings. Further, their application would result in a significant reduction in operational effectiveness.

4.0 RECOMMENDATIONS

It is recommended that:

A. The application of CADI to military trackshoes be rejected.

B. Development of process controls and specifications be continued for Cast Austempered Ductile Iron so that uniformity of material properties is improved.

C. CADI applications for other military vehicle parts be investigated - exclusively for parts that have operating

environments less severe than the trackshoe application and that are not designated as critical safety items for combat vehicles.

D. Any follow-on vehicular testing of the CADI trackshoe be accompanied by frequent and rigorous inspections of the trackshoe to detect metal failures before potential track separation causes loss of vehicle control.

5.0 DISCUSSION

5.1 Background

While the adoption of the forged T-158 track for the M1 tank series greatly increased the durability and therefore reduced the life cycle costs of the tank's track, current programs have been dedicated to the reduction of weight of the track. The current T-158LL track development program, for example, has demonstrated performance comparable to the T-158 track, but with 9 percent less weight. This amounts to over a one-half ton weight savings on the M1A1 tank. The life cycle cost reductions and the operational benefits of this size weight savings are significant. Cast Austempered Ductile Iron is less dense than wrought or forged steel and is normally less

expensive, thus the use of this material was proposed as a potential weight and cost reduction program.

5.2 Design

Starting from the design of the current production T-158 forged trackshoe (Appendix I), several changes were made to accommodate the casting process without adversely affecting design integrity. This effort was aided by SPD's proven expertise with the T-158 track and the photoelastic testing of the trackshoe conducted during the T-158LL trackshoe design effort. Original stress analysis of the T-158 trackshoe has previously been reported to TACOM. Continuing analysis of the T-158LL trackshoe will be reported at the conclusion of the current program. All three designs are pictured at Appendix II so that detailed comparisons can be made.

5.3 Manufacturing Process

Initially, ASTM A897-90 grade 175/125/4 was selected, however, this was revised to grade 150/100/7 in an effort to improve toughness while still providing tensile and yield strengths comparable with forged steel. Ultimately, the trackshoes produced did not exactly

match ei of the two specified grades, but were representative of the type of trackshoes that would be obtained in volume production. The trackshoes were within several of the international specifications for austempered ductile iron (Appendix VII), and the yield and tensile strengths were higher than required for grade 150/100/7 (Appendix II). Elongation achieved was low, but this was expected since it was measured on a sample bar of reduced size cut from the actual part rather than the test coupons. The manufacturing processes used to produce the T-158 CADI trackshoes are detailed below.

Base iron was melted in 2,000 lb. batches using a 1,000 cycle, 600 kw induction furnace. Alumina refractory was used throughout. The base charge consisted of a minimum of 20percent pig iron with the balance composed of a combination of wrought steel ingot and ductile iron remelt. Anticipated amounts of carbon, nickel, and silicon were added to the initial charge.

Once molten, samples were taken for spectrographic analysis. Final additions were then calculated and added as required. Re-sampling verified the desired base chemistry. The melt was quickly superheated to 2800^{0} F and tapped into a 2000 pound treatment

ladle. The ladle was designed with a height to diameter ratio of 3:1. Prior to tap, magnesium bearing nickel alloy was placed in the bottom of the treatment ladle (16 lbs. Inco Mag #4). Final chemistry is shown at Table I.

The iron was held in the treatment ladle until fuming subsided (from 1-2 minutes), after which it was transferred to the pouring ladle. During the transfer, ferro-silicon post inoculant was added to achieve a silicon pick-up of 0.40 percent. One 4 lb. ingot of Inco Mag was also added. Pouring temperature ranged from 2500 - 2560^{o} F.

Once the transfer was complete, the molds and test bars were poured as rapidly as possible. A stopwatch was started at the end of fuming in the treatment ladle. It was found that pouring should cease at 12 minutes into the process to insure that fading of the magnesium did not adversely affect the part quality. Each heat was immediately checked for effective nodularity at the end of the 12 minutes using standard metallographic sample preparation. Once assured of good nodularity, i.e., no significant fade of magnesium, the molds were allowed to be dumped and the castings removed for processing.

Molds were prepared of silica sand bonded with "Pep-Set", a standard

chemical binder. The shrink factor used in the mold patterns was one-sixteenth of an inch per foot. Castings were removed from the sand, shot blasted, de-gated, and finish ground. Several heat treatment trials were performed on test coupons before the desired microstructure was obtained. The final heat treatment report is attached at Appendix IV. The parts were machined after heat treatment. Chemistries of the various heats are shown below:

TABLE I

Heat #	C	Mn	Si	P	S	Ni	Cr	Mo	Mg
IB269	3.54	.13	2.35	.015	.010	1.28	.051	.006	.053
IB270	3.24	.11	2.66	.017	.009	1.23	.048	.006	.057
IB271	3.23	.09	2.57	.015	.009	1.26	.045	.003	.061
IB273	3.20	.10	2.89	.020	.010	1.28	.051	.007	.053
IB274	3.43	.08	2.52	.020	.009	1.43	.049	.006	.048
IB275	3.18	.08	2.43	.020	.009	1.27	.040	.006	.041

Weight percent

5.4 Process Controls

Intrinsically, castings are less homogeneous than forgings. For this reason, the specifications defining the CADI process are generically less stringent than those defining the forging process. Casting specifications attempt to define permissible limits of non-homogeneity (difficult to measure due to its non-linearity). Within these specifications, the manufacturer's goal is to tightly control the processes to the extent that the non-homogeneities that are always present in a casting still allow the desired mechanical properties of the part to be achieved. The following table describes the process controls required for the T-158 CADI trackshoe.

TABLE II

SIGNIFICANT CONTROL POINTS – T158 TRACK CADI

CHARACTERISTIC CHECKED	CHECKING FREQUENCY	QUANTITY CHECKED	CHECKING METHOD	PERSONNEL RESPONSIBLE	RECORD RETENTION	ACCEPTANCE CRITERIA
Chemical Composition	Every Heat	Chill Test Coupon	Spectrometer	Melting Supervisor	Melting Log Book SPC Charts for all Elements	C 3.2–3.8% AIM 3.6% Si 2.45–2.65% AIM 2.50% Mn .30% max P .03% max S .015% max Cu residual Ni 1.2–1.5% Mo residual Cr residual Ti residual Mg AIM .035%
Temperature	Every Ladle	N/A	Immersion Thermocouple	Pouring Helper	SPC Charts	AIM 2650 F
As Cast Dimensions	Every 1000 Molds	3 Castings	CMM	CMM Operator	Layout Record	Dimensions as Specified
Core Dimensions	Every 1000 Molds	3 Cores	Calipers	Operator	Layout Record	Dimensions as Specified
Node Count and Percent Nodularity	Every Ladle	Section of Runner from Last Mold Cast	Microscope	QA Technician	Pouring Log	Count > 100 Nodularity > 90%
Chemical Composition	Every Heat	Chill Test	Spectrometer	Melting Supervisor	Melting Log Book	See #1
Separately Cast Test Bars prepared at this step to accompany castings through heat treat.						
As Cast Dimensions	Every Lot	3 Castings	CMM	CMM Operator	Layout Record	Dimensions as Specified
Austenitize Temperature Cycle	Every Furnace Load	N/A	Furnace Charts	Heat Treat Supervisor	Furnace Record SPC Charts	Heat Treat Cycle as Specified
Austemper Temperature Cycle	Every Furnace Load	N/A	Furnace Charts	Heat Treat Supervisor	Furnace Record SPC Charts	Heat Treat Cycle as Specified
Mechanical Properties Charpy Impact @ –40 F Microstructure	Every Furnace Load	Specimens from Y–blocks	ASTM E8 ASTM E23 ASTM A247	Quality Assurance Supervisor	Heat Records SPC Charts	175/125/4 90% Bainite N/A See Note 1
Dimensions Hardness	Every Furnace Load	Castings Castings	Gages ASTM E10	Quality Assurance Supervisor	Inspection Records SPC Charts	Drawing 341–444 BHN

Note 1: ASTM A897–90 requires testing at 72 F of 4 samples. The highest average of any 3 of the samples should be 45 ft–lbs. Samples are unnotched.

5.5 Tooling

Sketches of tooling used in the casting of the trackshoes are contained at Appendix VI.

5.6 Testing

The CADI trackshoes were tested side-by-side with their forged T-158 counterparts by FMC's Corporate Technology Center. Testing included ballistic firing, tension/torsion testing, blast testing (to simulate mine detonations), tensile testing, and impact testing. CTC's test report is wholly contained at Appendix III, and only its conclusions are shown below.

5.6.1 Component Impact Testing. At ambient temperatures, the impact energy which induced a crack into the CADI trackshoes was 283 ft-lbs, while the forged trackshoe required 850-1000 ft-lbs to induce a crack. In cold temperatures, the CADI trackshoe cracked between 200-350 ft-lbs, while the forged trackshoe required 733 ft-lbs. Charpy impact test values were much larger for the forged samples than for the CADI samples. Charpy impact tests replicate the type of environment a trackshoe would experience in use when a tracked vehicle moves over a low wall, sharp rocks, road curbing, etc.

Several differences exist between Charpy tests for CADI materials and those for forgings. For example, Charpy values for CADI material are by specification taken on un-notched test coupons, whereas forgings are tested using v-notched parts. There is no guarantee that the values obtained from test coupons replicate those which could be obtained from the actual CADI part.

5.6.2 Tension/Torsion Fatigue Testing. All of the CADI trackshoes were tested to failure. All castings, whether CADI or not, are produced to a specification written to control the level of defects. All castings contain minor defects which will eventually lead to initiation of fatigue cracks under cyclic loading conditions. Each of the fatigue cracks originated at such a defect. Two of the forged trackshoes failed at cracks originating from a forging die vent hole location, while the other two forgings were not tested to failure. In those not tested to failure, the forging fatigue test was halted after accomplishing approximately 7.4 times the number of cycles achieved by the casting. The highest number of cycles tested was in excess of 735,000 cycles for the steel forging (without a failure), while the highest number of cycles any CADI trackshoe survived was 137,000 cycles. The cold temperature tension/torsion results showed much less durability for CADI trackshoes, which confirms TACOM's own report #1-VC-087-130-004 dated 5 April 1977. This report of cold

temperature vehicle testing of T-130E1 CADI track resulted in severe metal breakage of the track at a mean miles between failure (MMBF) of only 36.3 miles (Appendix V).

5.6.3 Tensile Testing. Although the ultimate tensile strength and the yield strengths of the forged trackshoe samples were a little higher than the CADI samples, the measurements of percent elongation and percent reduction in area were an order of magnitude higher than the CADI samples. This result reflects the increased ductility and toughness of the forged steel material and is consistent with published literature within the industry.

5.6.4 Ballistic/Blast Testing. Both kinetic energy and explosive shock comparisons were made on the forged and CADI trackshoes. The kinetic energy tests used the .30 calibre APM2, the .50 calibre APM2, and the 20 millimeter FSP (fragment simulating projectile) rounds at muzzle velocities of 2760 feet per second, 2940 FPS, and 2340 FPS respectively in both ambient and cold temperature environments. Other than a penetration hole, the forged shoes were not visibly damaged by the impacts of the three kinetic energy projectiles, while the CADI trackshoes suffered significant cracks, all of which would have resulted in track separations and mobility kills.

The blast tests used balls of C4 explosive at different distances from the trackshoes and of different weights. In the blast testing, the forged trackshoes suffered no damage in blasts that caused substantial damage to the CADI trackshoes.

5.7 Weight Analysis

Due to the material properties of Cast Austempered Ductile Iron, none of the components of the T-158 track were considered for weight reduction except the trackshoe itself. For the T-158 track pitch, the trackshoes contribute 32.5 pounds of the total pitch weight of 75.2 pounds, or 43 percent of the total pitch weight.

The CADI design reduced the trackshoe weight by .9 pounds (1.8 pounds per track pitch). This reduction results in a 2.6 percent reduction in track weight for the M1A1 tank (a total of 309 pounds).

In a separate but parallel effort (the T-158LL program), the weight savings accomplished through removal of steel from lower stressed areas of the T-158 track components resulted in a track weight reduction of 9 percent (a total of 1008 pounds). The T-158LL track, currently under vehicle test, has already demonstrated comparable

TABLE III

T-158 TRACK WEIGHT SUMMARY

	T-158	T-158LL	T-158 CADI
CENTERGUIDE ASSEMBLY	8.00	7.19	8.00
END CONNECTOR ASSEMBLY	2.88	2.88	2.88
PIN, RUBBERIZED	8.94	[illegible].47	8.94
TRACKSHOE, RUBBERIZED	16.24	13.88	15.24
Trackshoe, Machined Only	(12.9)	(10.2)	(12.0)
PAD ASSEMBLY W/NUT	5.55	5.55	5.55
PITCH	75.2	68.74	73.22
STRAND	5,866	5,362	5,711
VEHICLE SET	11,731	10,723	11,422
% DELTA	0%	-9%	-2.6%

ALL WEIGHTS ARE IN POUNDS

durability to the T-158 track. The weights are shown in Table III.

While continued development of the CADI T-158 trackshoe might result in additional weight savings, they would not approach the savings already achieved by the T-158LL trackshoe. In addition, the "thinning" of the trackshoe sections would amplify the complexity of casting the shoe; magnify the safety implications of a discontinuity of any type; demand a level of process control not yet demonstrated by the CADI industry; and would increase its vulnerability to impact loading and mines/shrapnel.

Based upon the above discussion and the results of testing at Appendix III of this report, it is not apparent that the CADI process offers any advantage in terms of weight savings for track.

5.8 Cost Analysis

The discussion on costs of the CADI trackshoe versus the forged T-158 trackshoe are presented as relative costs, since a great number of factors can influence the ultimate pricing of an item. Some of these factors are:

- Quantity to be produced
- Delivery schedule
- Vendor's perception of the ultimate market
- Capital equipment required/on hand
- Warranty provisions/risk
- Ease of processing
- Transportation
- Raw material
- Quality requirements

While ductile iron is usually less expensive than forged steel, application of the Cast Austempered Ductile Iron process within the track industry will produce several factors that will impact on the cost of CADI trackshoes. These factors are identified below:

- The process controls of the still maturing CADI industry inherently allow more product variability, even though the product may still be within the parameters of the specifications.

  For a critical safety item such as track, and with the CADI material inherently deficient in critical mechanical properties such as ductility and elongation, it is doubtful that a safe CADI trackshoe can be produced. Even if it can,

the process which would control its manufacture would need to be considerably tightened, and the result would be increased production cost.

- The secret to the CADI mechanical properties lies in the heat treatment, or austempering, of ductile iron. Current track metal manufacturers are not equipped or qualified for the austempering process. Therefore, track manufacturers would be forced to either abandon current heat-treaters in favor of the few companies currently qualified in the process or invest the resources required to become qualified. In either case, the costs of trackshoe heat treatment will increase, and associated transportation charges may also increase.

- Quality provisions would necessarily require that a rigorous internal inspection program (possibly including radiography) be conducted on CADI trackshoes in order to assure the user that the trackshoe would provide adequate fatigue life. This inspection would be additive to the external inspections (such as magnaflux) that forged trackshoes receive. Current track manufacturers are not equipped with the capability to conduct these internal inspections. Higher costs of quality assurance should be expected for the CADI trackshoes.

- The scrap industry is experiencing an increase in the presence of tramp alloys (chromium, manganese, microalloys, etc.) which are detrimental to producing the desired microstructure. It should be projected that scrap prices will rise, because ductile iron manufacturers will increasingly have to add virgin metals to the scrap to achieve usable chemistries of material.

- For the forged T-158 track, the combined trackshoe and the centerguide cost represent only 34 percent of the pitch cost. Therefore, only a dramatic cost reduction in these components will produce a significant reduction in overall track procurement cost.

5.8.1 Procurement Cost: Although ductile iron is generally recognized as less expensive than forged steel, <u>austempered</u> ductile iron is somewhere in between the two. For the right application - that is, for a part which is well served by the CADI process, the part should be less expensive than a steel forging. For a critical safety item operating in an environment involving significant impacts, extended cycling, and possibly cold temperatures (not to mention combat), the

CADI process is not a good application. Therefore, the procurement cost of obtaining a CADI trackshoe capable of consistently performing satisfactorily under these conditions is probably moot. If such a CADI part could be made, its procurement cost would be higher than a "normal" CADI part due to the requirement to adhere to tighter process controls and specifications.

A detailed analysis of the manufacturing cost for CADI trackshoes and trackshoe forgings is extremely difficult to obtain since the very nature of the data is competitive in nature and tightly controlled by the manufacturing sector. In many cases the data is useless without a complete list of relevant data required to define the circumstances. For the purposes of this report, a "normal" production scenario is assumed to be conducted with labor, overhead, and general and administrative charges to be the same for both the forging and the casting.

FORGING PROCESSES	CADI PROCESSES
Saw Billets	Melting/Pouring
Forging	Produce Cores/Molds
Shotblast	Grinding

Machining	Internal Inspection
Heat Treating	Magnetic Particle Inspection
	Austempering

The best estimate for costs of the forged trackshoe is $22-24, while the cost of the CADI trackshoe is $19-22. Relevant assumptions include:

a) All operations performed in-house except the austempering operation.
b) Quantity sufficient for two-shift operation.
c) Automated cores/molds production
d) Forging steel is priced at .28 cents/lb. while raw materials required for CADI is priced at .11 cents/lb.
e) Internal inspection of the casting is assumed to be ultrasonic inspection, not the more expensive x-ray inspection.

5.8.2 Life Cycle Cost: Life cycle cost encompasses the full range of costs attributable to the trackshoe throughout its life cycle, which classically includes Research and Development (R&D), Investment, Operations and Maintenance (O&M), and Disposal costs.

- Research & Development: The T-158 track is fully developed, and its second generation modification, the T-158LL track, is over 90 percent developed. Based upon the metallurgical, process, and material properties analyses conducted here, it is highly unlikely that a CADI trackshoe will ever meet <u>all</u> of the performance characteristics of the forged T-158 or T-158LL trackshoes even if large sums of R&D funding are spent.
- Investment: The U.S. Army has already invested heavily in the development of a cast steel and forged steel trackshoe industry. Setting up for production of a large volume of CADI trackshoes, with its requirement for highly specialized heat treatment facilities, would require a heavy investment for CADI trackshoes.
- Operations and Maintenance: The dominant factor determining the life cycle cost of track is durability (as measured by miles before replacement), since the requirement to replace a trackshoe stimulates requirements for maintenance, ordering, shipping, handling, and storage of the track, all of which are contained under the O&M heading.

The durability of the CADI trackshoe will not be as great as the forged T-158 trackshoe under any circumstances, and will probably be significantly less if the tension-torsion and impact strength component testing conducted during this program are any indication. In addition, the reduced survivability of the CADI track implies a reduced cost-effectiveness of the track under cold temperature or combat conditions regardless of the initial procurement cost.

- Disposal Costs: There should be little difference between the disposal costs of CADI track versus forged steel track. The only factor that is different, other than the variance in revenue from the sale of scrap (a minor factor), is the determination of when the trackshoe has ended its useful life. The forged steel T-158 and T-158LL trackshoes, if properly inspected, may be able to be rebuilt for future use. The CADI T-158, because of its greatly reduced fatigue life, cannot be considered for reuse regardless of the type of inspection contemplated.

Central to the cost analysis of the CADI trackshoe is a determination of the cost of creating and maintaining the industrial base for mobilization requirements. While the forged track industrial base already exists and is supported by the domestic forging clause, castings (of any type) are not protected. The costs of assuring that trackshoes are readily available when they are most needed far outweigh any conjectured procurement cost savings.

5.9 Safety Analysis

The metal track body of a track (any type) is considered a critical safety item because if the track metal fails while in use, the track will separate under load, causing control of the vehicle to be lost. The safety implications of an M1A1 tank or any tracked vehicle traveling at over forty miles an hour and out of control are obvious.

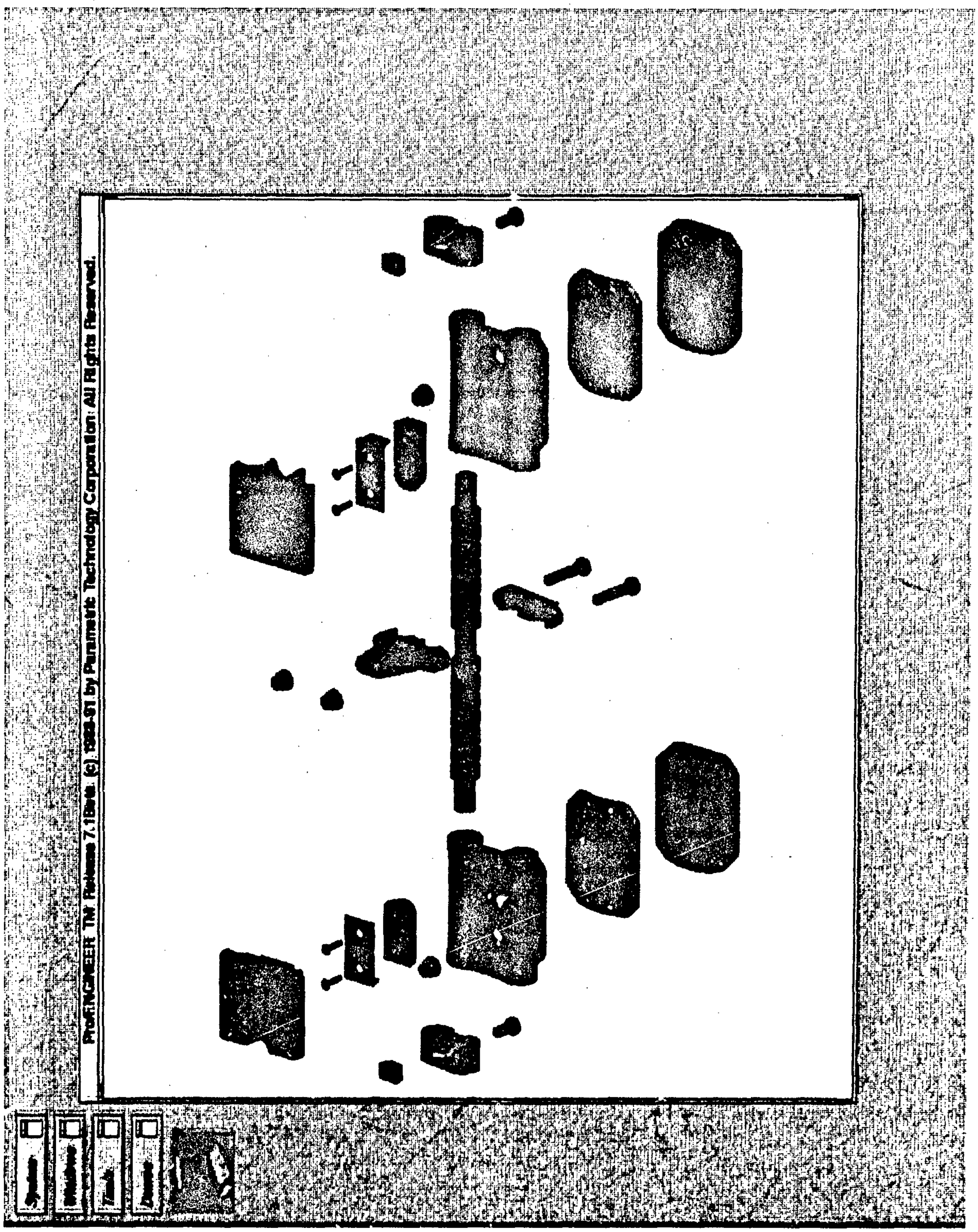
Proper track design requires that the principal mode of failure must be the rubber - normally the bushings. The reason for this is that rubber failures are easily detectable during routine inspections. Metal cracks are not, as they will normally be covered by dirt, mud, or the track rubber. A second reason for designing into the trackshoe this principal mode of failure is that even when failed,

the rubber bushing will normally allow for mission completion before replacement is absolutely necessary. A metal crack requires immediate replacement for safety reasons. The advantages of a rubber failure over a metal failure in combat are also obvious.

The material properties of CADI are presented elsewhere in this report and are not repeated here, but the data reflect an increase in the probability of a metal failure (due to impact loading or fatigue cycling) <u>prior</u> to failure of the rubber . The rubber on the T-158 has already demonstrated in one TACOM test the capability of lasting over 4,000 miles, which at a minimum equates to a fatigue cycling of over 426,000 cycles. This cycle count exceeds by 289,000 the maximum number of cycles endured by any of the CADI samples. This analysis does not consider any fatigue cycles induced by rocks, road wheelimpacts, passage over the idler wheel, or torsional stresses caused by turns, etc., but considers one cycle to be merely one complete revolution around the sprocket during straight ahead driving on a level road.

It is strongly recommended that any follow-on vehicular testing of the CADI track required in this project be accompanied by rigorous, frequent inspections of the trackshoe metal to preclude potential safety hazards to the crew or personnel near the vehicle.

Appendix I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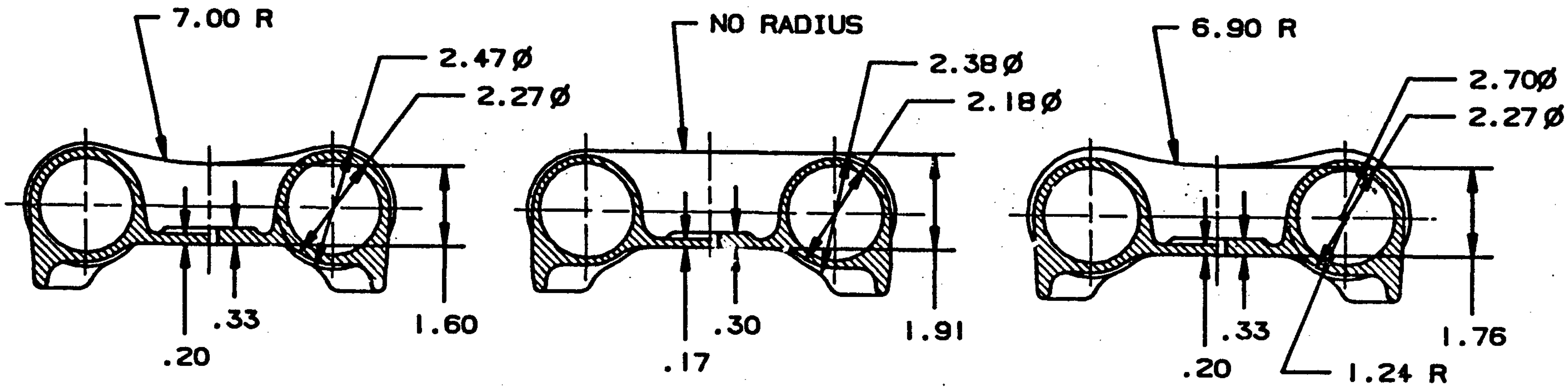
TRACKSHOE COMPARISON

T158, T158LL AND T158 CADI



T158 | T158LL | T158 CADI

NOTE: Chart values are averages of data shown in Table III of Appendix III.

TRACK CHARACTERISTICS	T158	T158LL	T158CADI
MATERIAL	AISI 8640	AISI 8640	ASTM-A897-90 150/100/7
TENSILE STRENGTH (psi)	167,080	167,080	157,650
YIELD STRENGTH (psi)	155,150	155,150	136,250
ELONGATION (%)	17.35	17.35	2.50
CHARPY IMPACT (70°)	37.02	37.02	72.8
CHARPY IMPACT (-40°)	36.70	36.70	46.1

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Appendix III

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December 18, 1991

MEL Report No. 910821

IMPACT, FATIGUE, AND MATERIAL COMPARISON OF FORGED AND CAST AUSTEMPERED DUCTILE IRON (CADI) T-158 TRACK AT AMBIENT AND LOW TEMPERATURE

Project No.: 3HJ310038

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ABSTRACT

Component Impact, Tension/Torsion Fatigue, and Ballistic Tests were conducted at ambient temperature and at low temperature on samples of forged steel and Cast Austempered Ductile Iron (CADI) T-158 track. Mechanical property measurements were also performed on samples of material taken from each type of track.

The ultimate tensile and yield strengths of the forged and CADI materials were similar, the forgings being slightly stronger. However the ductility and toughness of the forged material far exceeded that of the CADI.

The forged track blocks also outperformed the CADI track blocks in simulated life testing (Tension/Torsion Fatigue and Component Impact Testing), especially at low temperature.

Ballistic and explosive shock testing also confirmed the superiority of the forged track over the CADI track.

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BACKGROUND

The CADI (Cast Austempered Ductile Iron) track has been proposed as a possible weight and cost reducing replacement for the currently employed forged steel track. The cast material is manufactured in accordance with Spec. ASTM A897, and the forged material is a quench and tempered alloy steel (8640) per Spec. MIL-S-46172. Assembled T-158 track string segments incorporating cast and forged track shoe bodies were submitted by FMC Steel Products Division (SPD) for the evaluation.

OBJECTIVES

The purpose of this test was to compare the forged and the CADI components in Impact, Tension/Torsion Fatigue, and Ballistic Tests, and to compare the mechanical and metallurgical properties of the two materials.

TESTS PERFORMED

COMPONENT IMPACT TESTING

A weight on a horizontal pendulum (Figure 1) was raised and dropped on the pad side of the sample. The drop angle was gradually increased until a crack in the roadwheel side of the sample was visible.

The shoes tested had the bushings and pins installed, but did not have the pad installed or the roadwheel side rubber vulcanized in place. Each test item was clamped to an aluminum plate which was secured to the floor. A "prism" (Figure 2) with a triangular cross-section roughly 5 inches long was attached to the pendulum to concentrate the impact applied to the sample. The prism contacted the samples parallel to the track pins, centered between the pins, and toward the outside edge of the track block (Figure 3).

Samples were impacted at ambient temperature and after soaking overnight in an environmental chamber at -60° Fahrenheit.

TENSION/TORSION FATIGUE TESTING

A four pitch strand of track was installed in a fixture (Figure 4) which used a hydraulic actuator to cycle the tensile load on the sample between 5,000 and 50,000 pounds. In each cycle, the tensile load was maintained at 50,000 pounds while another hydraulic actuator applied torsional loads of +60,000 and -60,000 inch-pounds. The load application curves are shown in Figure 5.

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TENSION/TORSION FATIGUE TESTING - continued

For the low temperature testing, a foam insulation enclosure was fabricated around the test sample. Liquid nitrogen was introduced into the enclosure to maintain the temperature. A fan was connected to the chamber to encourage a consistent temperature distribution. The surface temperature at six locations on the sample and the air temperature at two places in the chamber were measured and recorded at regular intervals throughout the low temperature testing.

FRACTURE EVALUATION

All track shoe bodies that cracked during the tension/torsion fatigue testing were subjected to an evaluation of the fracture faces. The evaluations were performed to determine the cause of fracture initiation and the mode of fracture once the crack was initiated.

MECHANICAL PROPERTIES

Samples cut from actual track bodies were subjected to Tensile and Charpy Impact testing to determine the following properties:

- Ultimate Tensile Strength at ambient temperature
- Tensile Yield Strength at ambient temperature
- Elongation at ambient temperature
- Reduction in area at ambient temperature
- Charpy Impact Strength - Unnotched at ambient temperature
- Charpy Impact Strength - Notched at ambient temperature
- Charpy Impact Strength - Unnotched at -40°F
- Charpy Impact Strength - Notched at -40°F

METALLOGRAPHIC EXAMINATION

Cross sections from the failed forged and cast track blocks were prepared for metallographic examination to evaluate the as-cast microstructure (of the castings), heat treatment and the presence of any injurious material anomalies.

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BALLISTICS TESTING

A comparison of the effects of exposure to kinetic energy projectile impact and explosive shock on the two types of shoes was performed by the Armor Technology Department of FMC Corporation's Ground Systems Division.

The kinetic energy tests were conducted with three types of projectiles impacting shoes at ambient and low temperatures.

The explosive shock comparisons were conducted by detonating an explosive charge suspended a specific distance above the track pad side of a two pitch strand made up of one forged shoe assembly and one cast shoe assembly. The charge was positioned as close as possible to the center of the strand to expose both shoes to the same blast energy.

The Test Plan prepared by Ground Systems Division personnel for the explosive shock testing is included for reference in this report as Appendix A.

SAMPLES TESTED

The cast samples provided were reportedly of the latest pour and heat-treat process that would be used for production components.

The forged specimens were delivered in two shipments. The shoes received in the first lot were used for the impact tests, the first ambient temperature tension/torsion fatigue test (Sample #6), and the first low temperature tension/torsion fatigue test (Sample #2). The shoes in the second lot were used for the second low temperature tension/torsion fatigue test (Sample #4) and for the second ambient temperature tension/torsion fatigue test (Sample #8).

The material evaluations were performed on three sets of specimens cut from the shoes provided. One set was from the cast shoes and another set was sectioned from each of the two lots of the forged shoes.

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TEST RESULTS

COMPONENT IMPACT TESTING

The energies of the impacts which induced visible cracks in the samples are listed in Table I for the cast and forged shoes tested at ambient temperature and after soaking overnight in an environmental chamber at -60°F. The energy reported is the calculated mechanical potential energy of the pendulum assembly at the measured drop angle.

Several samples of each type of shoe were tested at each temperature condition to define the range of expected results, so that only two or three impacts were required to induce a crack in the specimens from which the listed data was collected. All of the cracks initiated at the edge of the pad mounting bolt hole (Figure 6).

TENSION/TORSION FATIGUE TESTING

The number of cycles accumulated before sample breakage and the results of a post-test failure analysis are included in Table II for each sample tested. The average surface temperature is included for the samples tested at low temperature.

Because the samples were enclosed in the insulation box for the low temperature testing, all of the tests were allowed to run until the specimen fractured. In most cases, the fatigue failure of one track block resulted in the failure of the other block in the track shoe assembly (Figure 7). All of the failures appear to have initiated at a stress concentration in the vertical (as the shoe is oriented when installed on a vehicle) web between the pin housings in the web nearest the track center guide (Figures 8 and 9).

The fractures in the cast shoes all originated at defects (voids or inclusions) in the castings. The fatigue failure of Sample #3 resulted in fractures in the pin housings of the other block in the shoe assembly and of one of the adjacent blocks. The break in the adjacent block exposed the shrinkage cavity shown in Figure 10.

The fracture initiation sites in the two forged shoes that failed were at one of the small round bumps formed on the top of the vertical web (Figure 11) at the vent hole locations. There may have also been a material defect at that location in Sample #6.

During the first ambient temperature test, substantial cracks (Figure 12) in several of the end connectors of the cast strand (Sample #5) were noticed after approximately 131,000 cycles. All of the end connectors were replaced at that time. The test continued until the sample failed at roughly 137,000 cycles.

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TENSION/TORSION FATIGUE TESTING - continued

The end connectors on the other three samples tested at ambient temperature were monitored for cracks throughout the test. In the first forged strand (Sample #6), small cracks were observed after approximately 87,000 cycles. After 89,000 cycles, a small crack in the test sample was apparent. The end connectors were replaced at 89,000 cycles. The test continued until the sample failed at about 114,000 cycles.

The end connectors on the second forged strand tested at ambient temperature were replaced after small cracks were noted at: 97,300 cycles, 172,560 cycles, 254,580 cycles, 341,750 cycles, and 423,580 cycles.

FRACTURE EVALUATION

Track shoe bodies that cracked during tension/torsion fatigue testing were subjected to a fracture evaluation. Four of the cast track sets and two of the forged sets were evaluated. The purpose of the evaluation was to determine the fracture initiation sites and the mode of fracture for each cracked track set.

Visual and Magnetic Particle Examination

All fractured track shoe bodies were visually examined. The overall failure mode was apparently the same for all track sets. One of the two track blocks initiated a crack, which propagated until that part completely failed, leading to the failure of the adjacent track block. Magnetic particle inspection did not reveal any evidence of large surface flaws such as laps, seams, shrinkage, or surface porosity contributing to the fracture initiation of any of the shoes.

Fracture Examination

The fracture surfaces of the cracked cast track shoe bodies were examined visually and with the scanning electron microscope (SEM). All fractures initiated in the raised rib section of the track block (Figures 8, 9, and 13) at small subsurface flaws (Figures 14, 15, and 16). Qualitative chemical analyses indicated that the inclusions were oxide type inclusions (slag). Closer examination of the fracture initiation areas revealed striations indicative of fatigue cracking. One of the failed track blocks exhibited a large area containing shrinkage (Figure 10). However, the shrinkage cavity did not contribute to fracture initiation.

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Fracture Examination - continued

The fracture faces of the forged track blocks were examined optically and with the scanning electron microscope. Both failed track blocks exhibited crack initiation in the same location; that being the raised rib section (Figure 17). The failed track block of Sample #2 had one fracture initiation site in the rib near the center guide and another in the rib near the end connector. SEM examination indicated that one fracture initiated at the surface of the forging (Figure 18), while the other initiated at a surface defect (Figure 19) located at one of the small dimples (Figure 11) that were reportedly formed by vent holes in the forging die. The defects appeared to be small forging laps. Both Sample #2 and Sample #6 exhibited striations (Figure 20), indicating that crack propagation was by fatigue.

METALLOGRAPHIC EXAMINATION

Cross sections from the failed forged and cast track blocks were prepared for metallographic examination to evaluate the as-cast microstructure (of the castings), heat treatment, and the presence of any injurious material anomalies. All cross sections were taken from areas adjacent to the fracture initiation sites to determine if any microstructural anomalies contributed to the cracking.

The microstructure of the two observed forgings consisted of tempered martensite, indicative of a correctly heat treated component (Figure 21). There was little evidence of decarburization and no evidence of injurious material anomalies such as laps or excessive concentrations of nonmetallic inclusions anywhere in the prepared cross sections.

The microstructure of the three castings exhibited a matrix of bainite, indicating that the castings had received an austempering heat treatment. However, the castings exhibited extremely different graphite shapes. The graphite from casting Sample #5 exhibited an even dispersion of small, spheroidal graphite nodules (Figure 22). Such graphite is considered optimum for ductile iron. The casting from Sample #3 exhibited a somewhat larger and blockier graphite nodule (Figure 23). Such graphite shape is also normally considered acceptable. However, the graphite shape from Sample #1 exhibited exploded graphite (Figure 24). Such a structure can adversely affect the mechanical properties of the casting and is normally considered not an acceptable condition.

MECHANICAL PROPERTIES

The results of the Tensile testing and the Charpy Impact testing are presented in Tables III and IV. Typical stress-strain curves are shown in Figure 25. The specimens from the original lot of forged shoes are labeled Forged #1A, #2A, and #3A. The specimens labeled Forged #4B, #5B, and #6B were cut from forged shoes of the second shipment.

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BALLISTICS TESTING

The detailed report prepared by Ground Systems Division personnel on the explosive shock and kinetic energy projectile impact comparison testing is included in this report as Appendix B.

Kinetic Energy Projectile Impact Testing

Other than the penetration hole, the forged shoes were not visibly damaged by the impacts of the three sizes of kinetic energy projectiles. The impacts of the larger two projectiles at the same velocities resulted in significant cracks in the cast shoes.

Explosive Shock Testing

The forged shoes were not visibly affected by blasts that caused substantial damage to the cast shoes.

DISCUSSION

The cracking of the end connectors may have had some effect on the results of the ambient temperature tension/torsion testing. The cracks in the track blocks generally initiated in the web near the center guide on the roadwheel side of the track blocks. It is possible that the cracks in the end connectors increased the load carried by the center guide during testing.

Cracks in the end connectors were not noted in three of the low temperature tests. There were cracks in two of the end connectors on the forged strand that was tested for 735,000 cycles.

Except for elongation, the mechanical properties attained from the cast material met the ASTM A897 requirements for Grade 150/100/7 CADI (see Tables III and IV). However, the reduced size tensile samples had been cut from the production castings rather than from separately cast test coupons. Typically, for cast irons, specimens cut from castings will have lower yield strength and elongation properties than separately cast coupons. This effect is not generally a problem with forgings.

The modulus, toughness, and ductility properties (as measured by Charpy Impact, Elongation, and Reduction in Area) of the CADI material were significantly lower than for the forged steel. These properties were probably major contributors to the lower fatigue life of the cast shoes.

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DISCUSSION - continued

The material flaws noted at the initiation sites of the cast track blocks were not large and should be considered normal for a sand cast material. No conventional inspection method would be able to reveal such small material anomalies.

The small laps noted at the fracture initiation sites of the forged track block were also small. The size and severity of the laps were similar to the large oxide inclusions noted in the cast blocks, indicating that the reduction in fatigue properties noted between the cast and forged components were due primarily to the mechanical property differences between the two materials.

There was a large variance in internal quality and general microstructure between different cast track blocks. One casting exhibited a large shrinkage cavity and there were significant differences in graphite nodule size and shape. Such variances indicate variability in the foundry processes used to manufacture the castings.

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TABLE I

RESULTS OF IMPACT TESTING

SAMPLE TYPE	SAMPLE TEMPERATURE*	IMPACT ENERGY WHICH INDUCED A VISIBLE CRACK (± 20 ft-lb)
Cast	Ambient	283
Cast	Ambient	283
Cast	Ambient	283
Cast	Ambient	283
Cast	Ambient	283
Forged	Ambient	860
Forged	Ambient	924
Forged	Ambient	988
Forged	Ambient	988
Cast	Cold	219
Cast	Cold	283
Cast	Cold	315
Cast	Cold	347
Forged	Cold	733
Forged	Cold	733
Forged	Cold	733

* The samples tested at the cold temperature were soaked overnight at -60°F.

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TABLE II

RESULTS OF TENSION/TORSION FATIGUE TESTING

SAMPLE #	SAMPLE TYPE	TESTING TEMP. (± 5 °F.)	# OF CYCLES (± 1000)	COMMENT
1	Cast	-45	120,000	Fatigue failure originating at a defect in the casting
2	Forged	-45	220,000	Fatigue failure originating at a forging die vent hole location
3	Cast	-50	97,500	Fatigue failure originating at a defect in the casting
4	Forged	-52	735,000+	Test terminated; no cracks evident
5	Cast	Ambient	137,000	Fatigue failure originating a defect in the casting
6	Forged	Ambient	114,000	Fatigue failure originating at the forging die vent hole location or at a "lap" near the vent hole
7	Cast	Ambient	59,000	Fatigue failure originating at a defect in the casting
8	Forged	Ambient	436,000+	Test terminated; no cracks evident

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TABLE III

RESULTS OF TENSILE SAMPLE TESTING

SPECIMEN	ULTIMATE TENSILE STRENGTH (± 5 KSI)	YIELD STRENGTH, 0.2% OFFSET (± 5 KSI)	PERCENT ELONGATION MEASURED IN 1.4 INCHES (± 0.5%)	PERCENT REDUCTION IN AREA (± 0.5%)
Cast #1	148.6	138.5	1.5	2.0
Cast #2	166.7	134.0	3.5	5.0
Forged #1A	158.4	146.8	18.0	52.5
Forged #2A	169.7	158.5	18.0	52.0
Forged #4B	174.4	162.5	16.4	56.5
Forged #5B	165.8	152.8	17.0	55.5

All tensile tests were performed on 0.357" diameter standard tensile samples cut from the thickest available sections of the track block castings (the junction of the grouser and boss).

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TABLE IV

RESULTS OF CHARPY IMPACT TESTING

ENERGY MEASURED TO FRACTURE TEST SPECIMEN (ft-lb)

SPECIMEN	At Ambient Temperature		At -40 degrees Fahrenheit	
	Unnotched	Notched	Unnotched	Notched
Cast #1	85.7	4.9	57.6	4.3
Cast #2	44.4	5.0	70.1	4.6
Cast #3	88.4	4.9	10.6	4.3
Forged #1A	>128	33.4	>128	31.3
Forged #2A	n/a*	28.8	n/a*	30.3
Forged #3A	n/a*	34.3	n/a*	35.3
Forged #4B	>128	43.3	>128	39.7
Forged #5B	n/a*	41.2	n/a*	44.1
Forged #6B	n/a*	41.1	n/a*	39.5

*Only one unnotched forged sample of each type was tested at each temperature. Since these specimens did not fracture when tested at the full capacity of the testing apparatus (128 ft-lb), the other samples were not tested.

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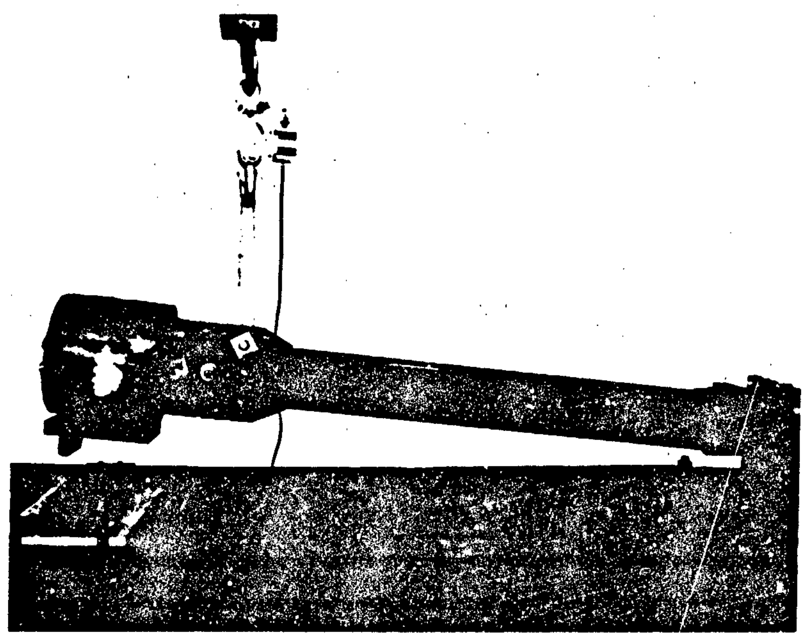

FIGURE 1

IMPACT TEST SET-UP

When the electric quick release (shown at the top of the photo) is activated, the weight on the pendulum falls on the sample.

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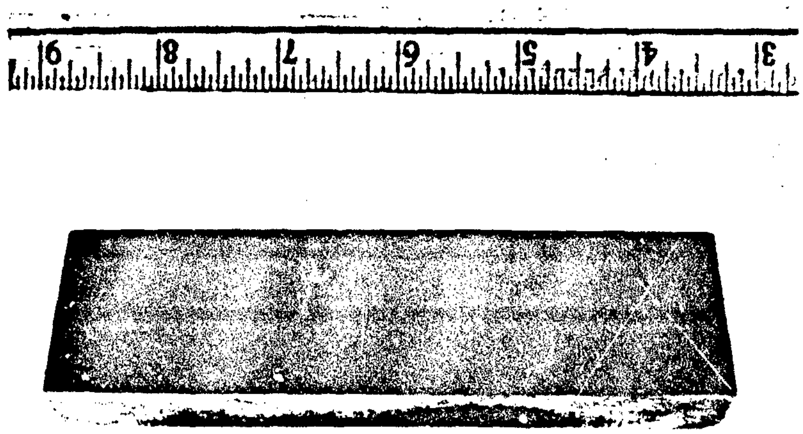

FIGURE 2

IMPACT TEST "PRISM"

The prism is attached to the weight to concentrate the impact on the sample.

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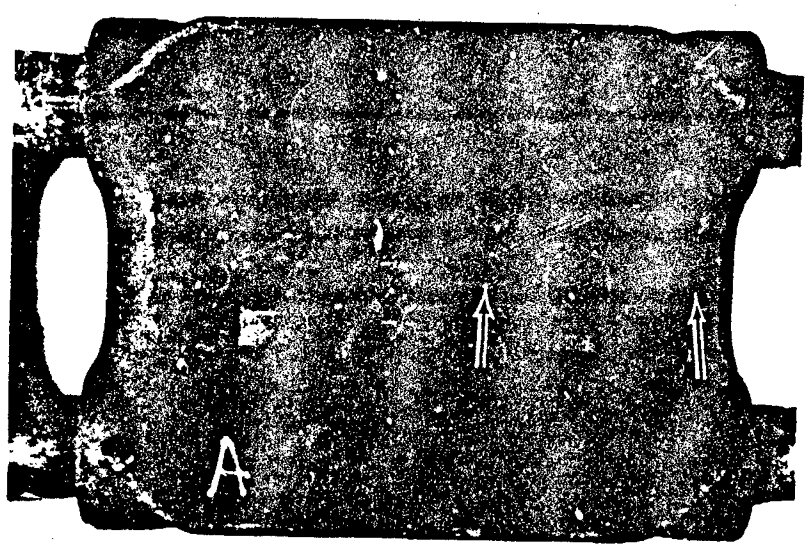

FIGURE 3

LOCATION OF IMPACT ON TRACK SHOE

The prism contacted the samples parallel to the track pins, centered between the pins, and toward the outside edge of the track block.

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FIGURE 4

TENSION/TORSION FATIGUE TEST SET-UP

A hydraulic actuator (the piston and load cell of which are visible in the ride hand side of the photo) cycled the tensile load between 5,000 and 50,000 pounds. The hydraulic actuator shown in the bottom of the photo applied a torsional load of ±60,000 inch-pounds.

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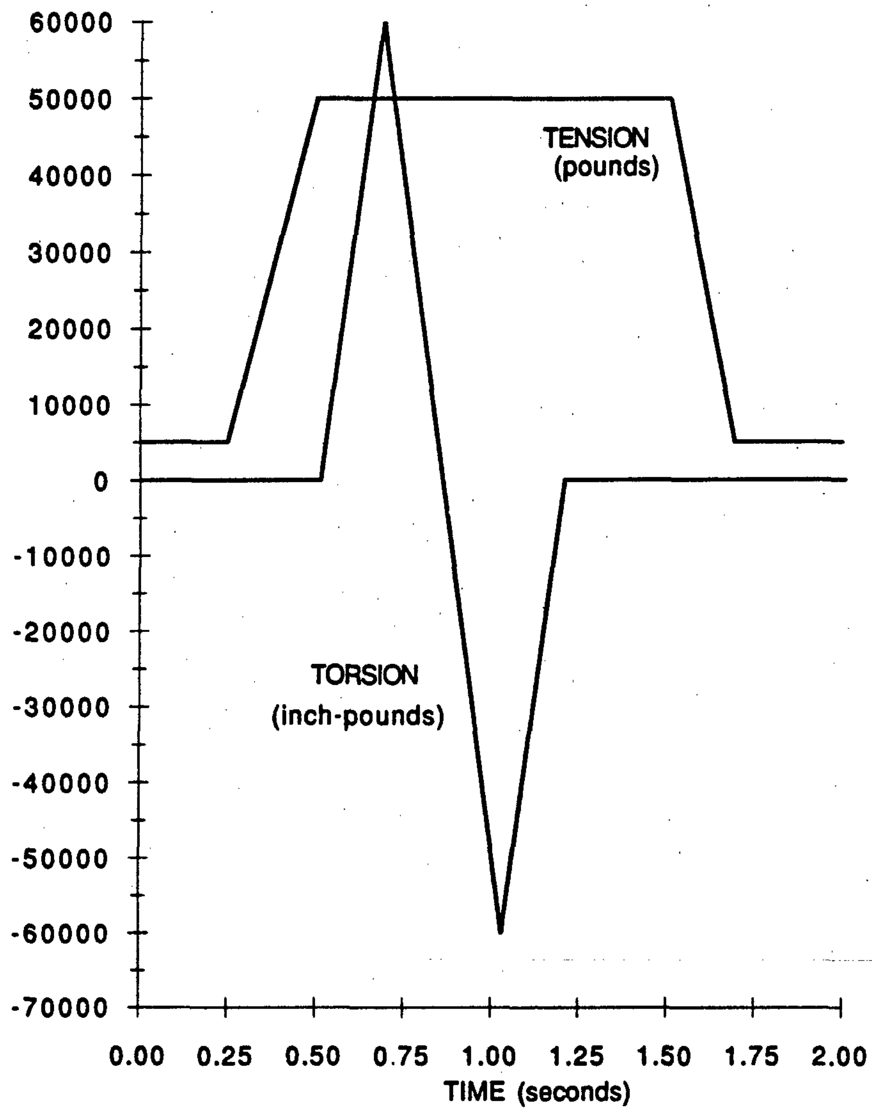

FIGURE 5

TENSION AND TORSION LOAD APPLICATION CURVES

One cycle of the Tension load (in pounds) and the Torsion load (in inch-pounds) plotted against Time (in seconds).

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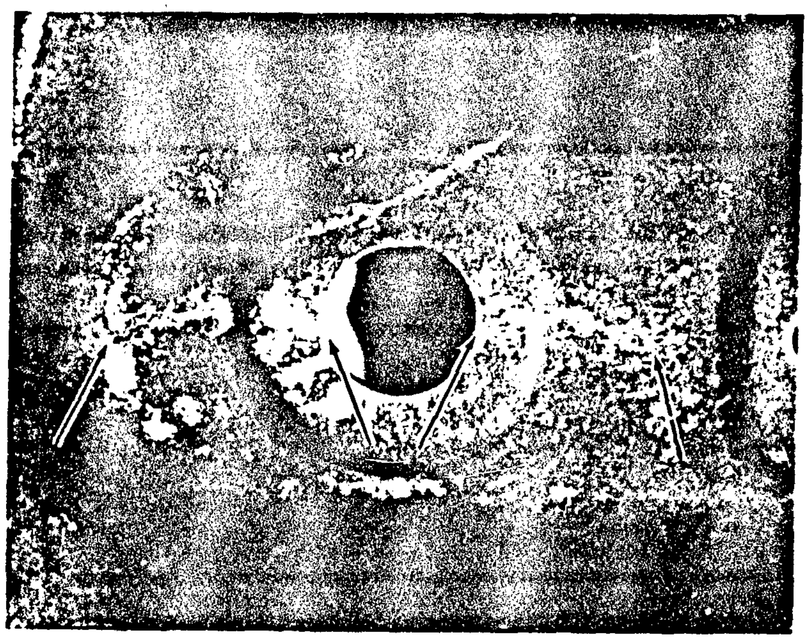

FIGURE 6

IMPACT INDUCED CRACK IN CAST TRACK SHOE

Cracks in the roadwheel side of the shoe, originating at the pad mounting bolt hole, after impact of approximately 283 ft-lb on the pad side of the shoe.

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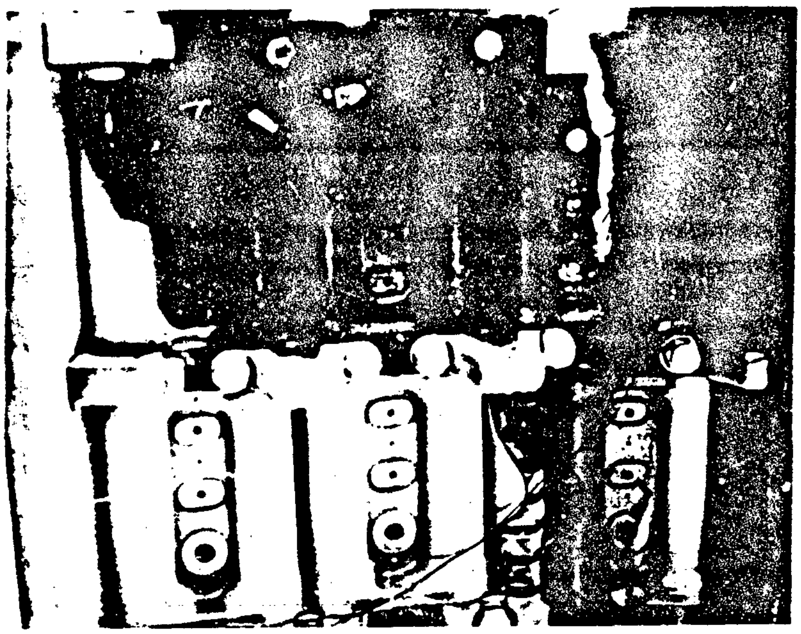

FIGURE 7

FAILURE OF TENSION/TORSION FATIGUE TEST SAMPLE

This cast test item (Sample #1) failed after 120,000 tension/torsion cycles at low temperature. The failures of the other specimens were similar.

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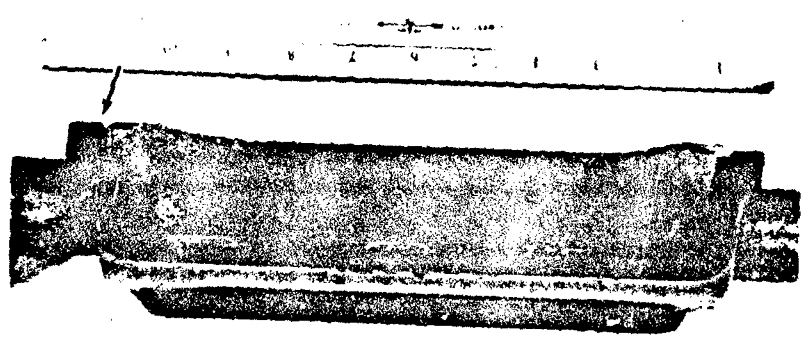

FIGURE 8

LOCATION OF FRACTURE INITIATION IN CAST SHOE (SAMPLE #1)

The arrow indicates the general area of the defect where the fracture originated. The initiation site in this particular shoe was found to be a small oxide inclusion.

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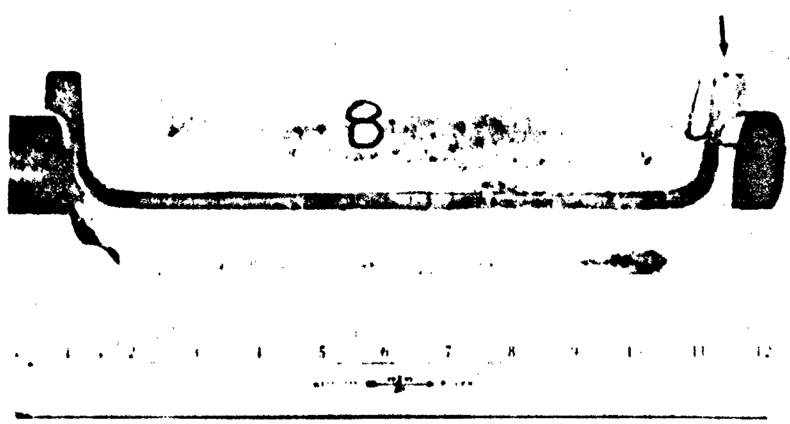

FIGURE 9

LOCATION OF FRACTURE INITIATION IN CAST SHOE (SAMPLE #5)

The arrow indicates the general area of the defect where the fracture originated. The other tension/torsion fatigue test samples failed in similar locations.

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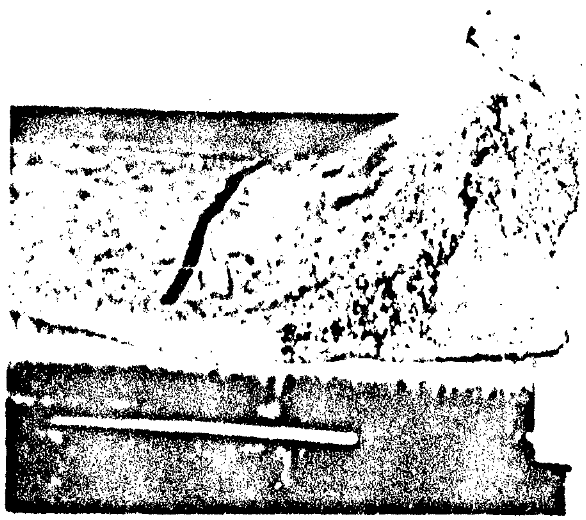

FIGURE 10

SHRINKAGE CAVITY IN CAST SPECIMEN

This shoe broke as a result of the fatigue failure of an adjacent shoe during the tension/torsion fatigue testing of Sample #3.

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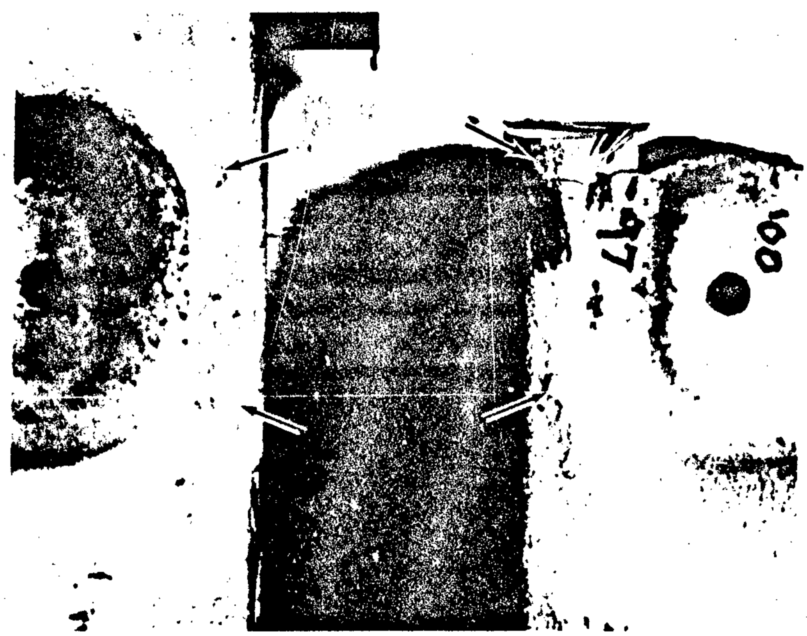

FIGURE 11

LOCATION OF VENT HOLES ON FORGED SHOE (SAMPLE #6)

Fatigue failures in the forged shoes initiated at one of these raised areas on the vertical web between the pin housings.

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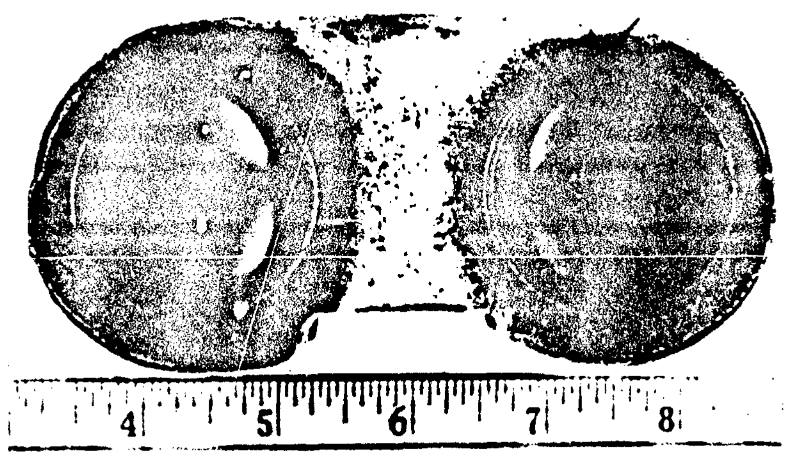

FIGURE 12

CRACKS IN END CONNECTOR

The end connectors were removed from the cast track strand (Sample #5) after 131,000 tension/torsion cycles at ambient temperature. Several of the other end connectors had cracks similar to the ones shown in this photo.

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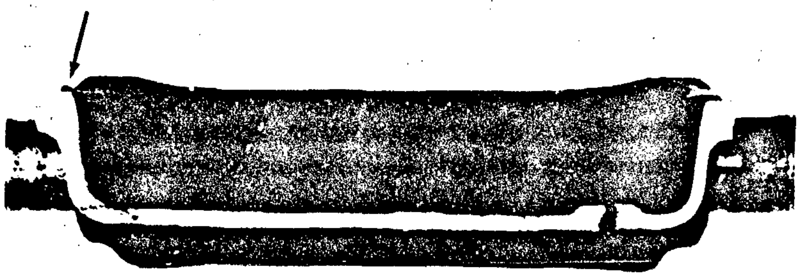

FIGURE 13

LOCATION OF FRACTURE INITIATION IN CAST SHOE (SAMPLE #7)

Fracture initiation site was at an oxide inclusion in the raised rib area.

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FIGURE 14

FRACTURE INITIATION SITE OF CAST TRACK BLOCK

Close-up view of oxide inclusion noted in Figure 13.

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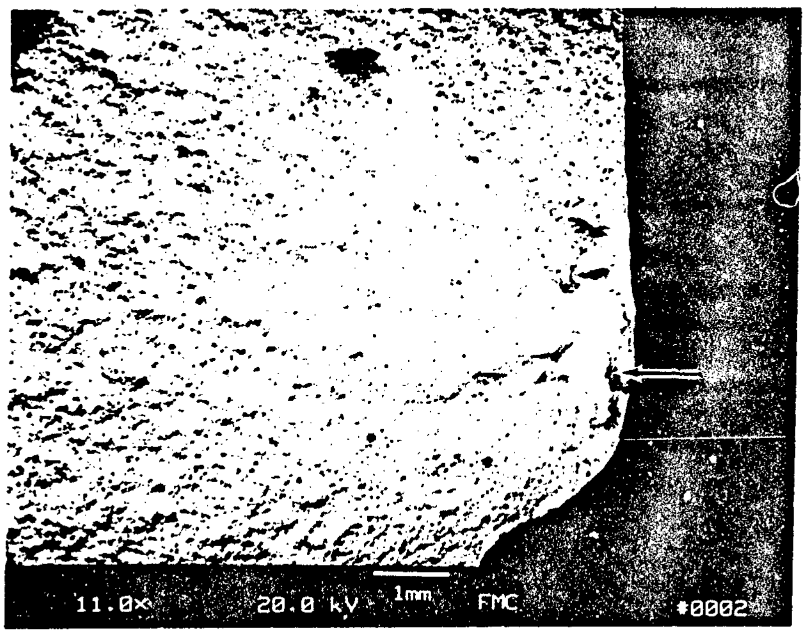

FIGURE 15 **MAG = 11.0X**

FRACTURE INITIATION SITE OF CAST TRACK BLOCK (SAMPLE #3)

Initiation site was an oxide type inclusion.

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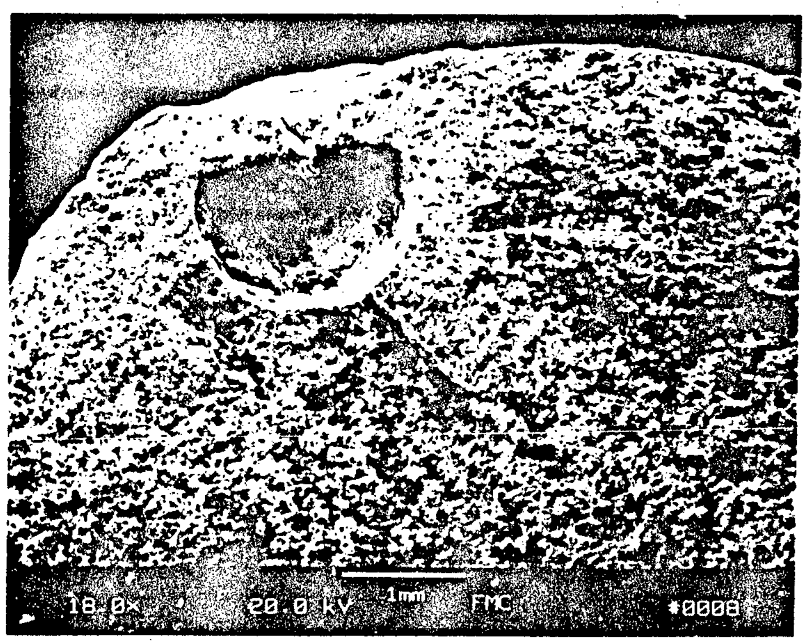

FIGURE 16 **MAG = 18X**

SUBSURFACE FLAW IN CAST TRACK BLOCK (SAMPLE #1)

Flaw was a hole from an oxide inclusion. Crack initiation was at this flaw during tension/torsion fatigue testing.

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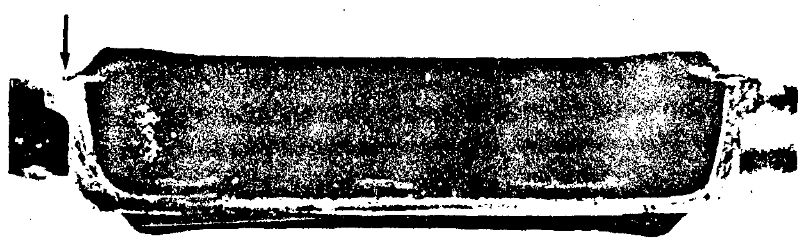

FIGURE 17

LOCATION OF FRACTURE INITIATION IN RIB NEAR CENTER GUIDE OF FORGED SHOE (SAMPLE #2)

The arrow indicates the area of the defect where the fracture originated.

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FIGURE 18 MAG = 19X

FRACTURE INITIATION OF CRACK IN FORGING

Close-up view of fracture initiation shown in Figure 17.

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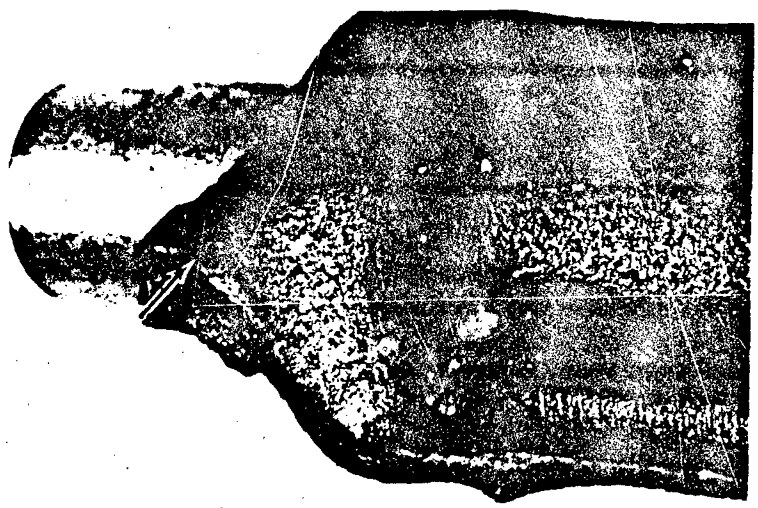

FIGURE 19 MAG = 0.8X

LOCATION OF FRACTURE INITIATION IN RIB NEAR END CONNECTOR OF FORGED SHOE (SAMPLE #2)

Crack initiated at a small lap on the surface of the forging at a small bump on the forging surface caused by vent holes in the forging die.

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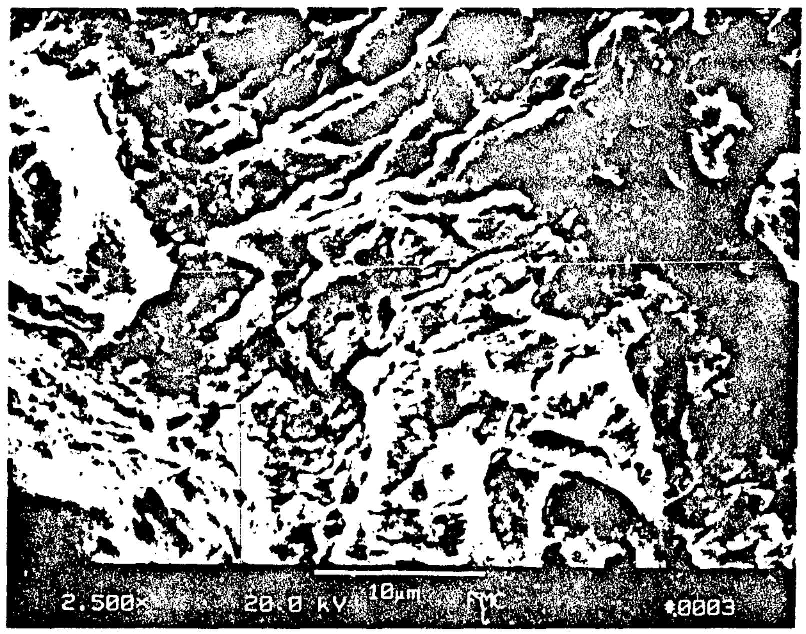

FIGURE 20 MAG = 2500X

FATIGUE STRIATIONS FROM INITIATION AREA OF FORGING CRACK

Striations are indicative of fatigue.

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FIGURE 21 MAG = 250X

MICROSTRUCTURE OF FORGING

Microstructure consisted of tempered martensite, indicative of a correctly heat treated component. There was little evidence of decarburization and no evidence of injurious material anomalies such as laps or excessive concentrations of nonmetallic inclusions

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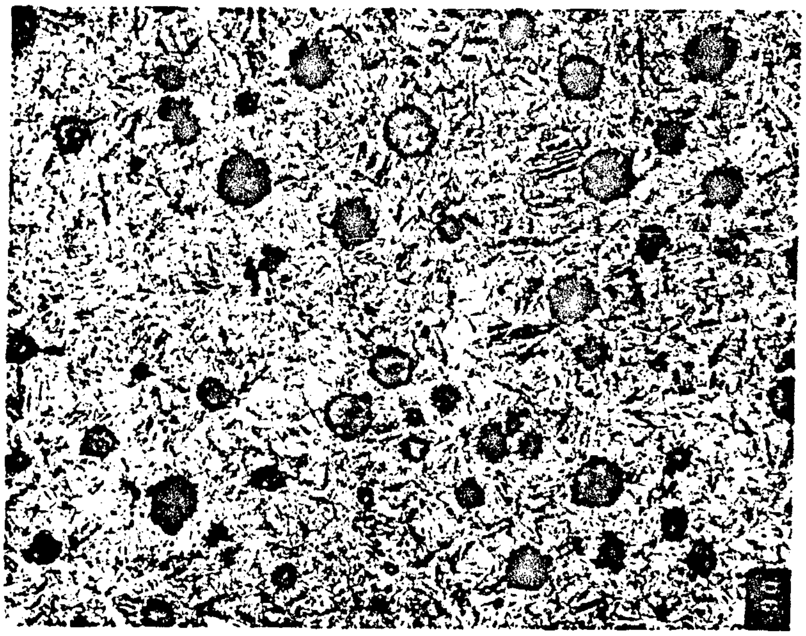

FIGURE 22 MAG = 250X

MICROSTRUCTURE OF CASTING SAMPLE #5

This microstructure was consisted of graphite spheroids in a matrix of bainite. The bainitic microstructure indicated that the casting had been properly heat treated (austempered). The graphite was an even dispersion of small, spheroidal graphite nodules. Such graphite is considered optimum for ductile iron.

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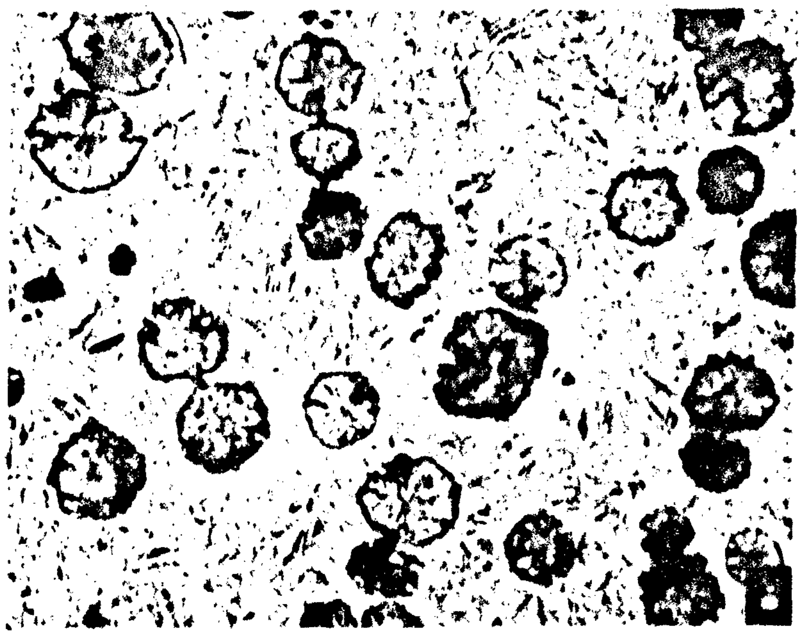

FIGURE 23 MAG = 250X

MICROSTRUCTURE OF CASTING SAMPLE #3

This microstructure was consisted of graphite spheroids in a matrix of bainite. This casting exhibited a somewhat larger and blockier graphite nodule than that shown in Figure 22. Although not optimum, such a graphite shape is also normally considered acceptable.

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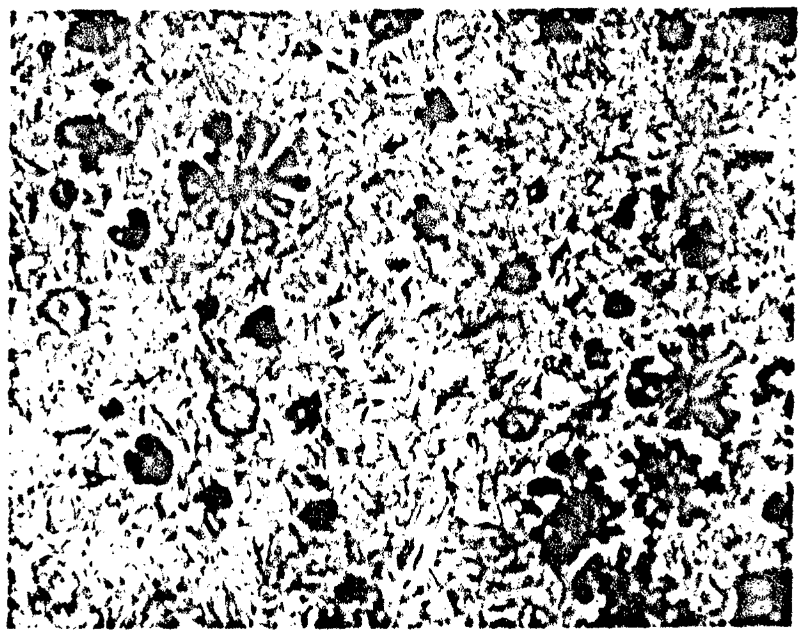

FIGURE 24 **MAG = 250X**

MICROSTRUCTURE OF CASTING SAMPLE #1

Microstructure was exploded graphite nodules in a matrix of bainite. The bainitic microstructure indicated that the casting had been properly heat treated (austempered), however, the exploded graphite is not a desirable structure and can lead to lowered mechanical properties.

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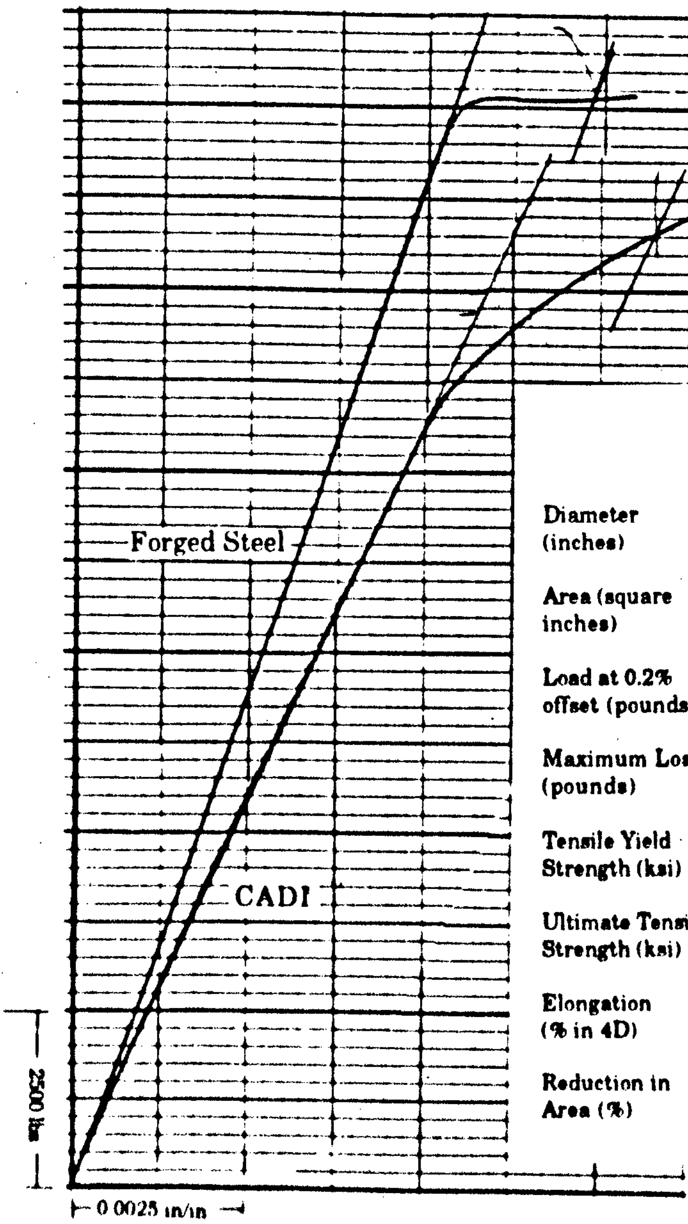

	CADI Specimen	Forged Specimen
Diameter (inches)	0.349	0.3485
Area (square inches)	0.0957	0.954
Load at 0.2% offset (pounds)	13,250	15,125
Maximum Load (pounds)	14,221	16,188
Tensile Yield Strength (ksi)	138.5	158.5
Ultimate Tensile Strength (ksi)	148.6	169.7
Elongation (% in 4D)	1.5	18.0
Reduction in Area (%)	2.0	55.5

FIGURE 25

TYPICAL STRESS-STRAIN CURVES FOR CADI AND FORGED TENSILE SPECIMENS

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APPENDIX A

TEST PLAN 10953

EXPLOSIVE SHOCK COMPARISON OF FORGED AND CAST TRACK SHOES

Explosive Shock Comparison Test of Forged And Cast Track Shoes
Test Plan Number 10953

November 1991
SPA 965-700-001

FMC Corporation
Ground Systems Division
Ballistic Technology Laboratory
Hollister, California

Prepared By;

David A. Schade

Reviewed By;

Tony Lee

Ken Keck 22 Nov 91

1.0 Objective

The objective of testing is to compare the performance of forged and cast T-158 track shoes when subjected to explosive shock loads. This is not a mine test. ~~However~~ it will simulate the shock load on the track shoe from a small mine and provide a means of comparing the damage sustained by forged and cast track shoes.

2.0 Test Preparation

Test materials and equipment to be used in this test will be supplied as listed below.

Corporate Technology Center (CTC)

- 4 sets of linked forged and cast shoes
- 3 sets of linked forged shoes

(Cast shoes have the word "prototype" cast into them in raised letters and are painted olive drab. Forged shoes are painted sand.)

Ballistic Technology Laboratory (BTL)

- Test Arena with personnel bunker
- Fire truck and extinguishers
- Detonation cord and controls
- Forklift
- Ambulance
- Pick-up truck (rental)
- 35mm camera and film
- Sand
- Crew supplies
- Detonators boosters and explosives
- Armored camera stands
- Tractor
- Transit and Level

Video Department

- Video cameras
- Video tape

3.0 Test Setup and Procedure

The track shoes will be subjected to blast from explosive suspended above them. A linked cast and forged shoe will be placed under the explosive. The shoes will be placed top down on a bed of sand to provide a constant backing in the test.

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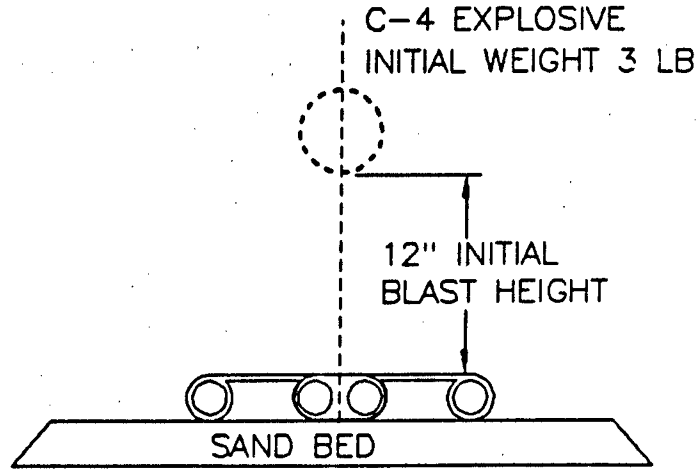
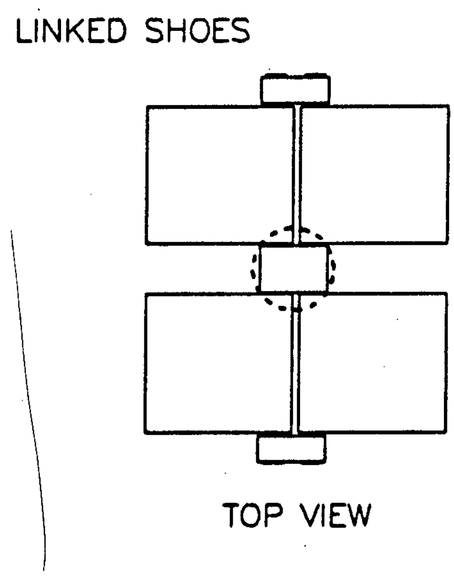
Figure 1.

TRACK SHOE BLAST TEST COMPARISON
FIGURE 2.



SIDE VIEW



TOP VIEW

TRAKSHOE

The test set up is shown in Figure 1. Four sets of linked cast and forged shoes are available for testing. Three sets of linked forged shoes are available to determine an appropriate burst height and explosive weight. In the initial test a 3 pound ball of C-4 explosive will be suspended 12" above a linked set of forged shoes. The damage from this test will be evaluated to determine an appropriate burst height and explosive weight for the linked cast and forged shoe test. Additional tests may be done on linked forged shoes to set the burst height and C-4 weight. Once the test configuration is determined, up to 4 tests will be conducted on the linked forged and cast shoes. Multiple tests will evaluate the consistency of the behavior of the shoes.

4.0 Test Documentation

Video cameras will document the condition of the shoes before, during and after testing. Still photographs will also be taken. Test results will be recorded on the attached form. An unclassified memo report documenting test data and photos will complete this work. After testing, the shoes will be returned to CTC for material evaluation.

TRACK SHOE COMPARISON TEST
SPA 965-700-001

DATE____________
FR 10953-________

TRACK SHOE COMBINATION____________________________

EXPLOSIVE HEIGHT_________ C-4 EXPLOSIVE WEIGHT__________

POST TEST TRACK CONDITION (deformation, cracks, breakage);

SKETCH;

Photographed By_____________________

Recorded By_________________________

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APPENDIX B

FMC BALLISTIC TEST REPORT 91-019

BALLISTIC COMPARISON OF

FORGED AND CAST TRACK SHOES

Ballistic Comparison of Forged and Cast Track Shoes
FMC Ballistic Test Report 91-019

December 1991
SPA 965-700-001

FMC Corporation
Ground Systems Division
Armor Products and Applications
Santa Clara, California

Prepared By,

David A. Schade 13-Dec 91
David A. Schade

Reviewed By,

13 Dec 91
Ken Keck

Anthony P. Lee

1.0 Objective

The objective of testing was to compare the performance of forged and cast track shoes when subjected to ballistic threats. The shoes were compared in blast tests and with kinetic energy projectiles at ambient and cold temperatures.

2.0 Background

A ductile steel casting material is being considered to for use in T-158 track shoes for the M-1 tank. Currently, the track shoe is made from a steel forging. Experience with other forged and cast materials indicates that forgings typically have superior ballistic performance to castings.

Kinetic energy tests were conducted with .30 APM2, .50 APM2 armor piercing rounds and 20mm fragment simulating projectiles (FSP) to simulate artillery fragments. One series of tests was conducted at ambient temperature (52°F to 63°F) and one was conducted at -40°F.

Blast test comparison was conducted by detonating an explosive above a cast and forged shoe and comparing the relative damage. It was not to simulate a specific mine threat, but provided a fair and efficient means of comparing the cast and forged shoes under ballistic shock.

3.0 Conclusion

The ballistic performance of the forged track shoes was superior to the cast shoes. Cast shoes sustained heavy cracks and breakage when subjected to blast, .50 APM2 and 20mm FSP. In some cases, cracks extended all the way across the track. Cracks and damage in the cast track posed a high probability of track separation and a mobility kill.

The forged shoes sustained no damage other then the projectile penetration hole. Forged shoes sustained no damage even when tested with twice as much explosive as the cast.

There was no significant difference in the extent of cast shoe damage at ambient or cold temperature.

4.0 Results

The results of testing are summarized in Table 1.

TEST RESULTS, Table 1.

Test	Shoe Type	Result	Firing Record	Figure
.30 APM2 at 60°F	Cast	no cracks or breakout	91186	1
	Forged	no cracks or breakout	91187	
.30 APM2 at -40°F	Cast	no cracks or breakout	91184	2
	Forged	no cracks or breakout	91185	
.50 APM2 at 53°F	Cast	cracks along 3/4 of shoe, sections broken out	91178	3
	Forged	no cracks or breakout	91179	
.50 APM2 at -40°F	Cast	cracks all the way across shoe, separation 1/16 to 1/8"	91181	4
	Forged	one short crack due to high hit*, no cracks in shot 2	91180	
20 FSP at 63°F	Cast	cracks along 3/4 of shoe, sections broken out	91188 91190	5
	Forged	no cracks or breakout	91189	
20 FSP at -40°F	Cast	cracks along 3/4 of shoe, sections broken out	1182	6
	Forged	no cracks or breakout	91183	
3 lb C-4 at 6"	Forged & Forged	no damage to shoes, links or pins - rubber pads shifted	10953 -1	7,8
6 lb C-4 at 3"	Forged & Forged	no damage to shoes, links cracked and separated	10953 -2	9,10, 11
3 lb C-4 at 3"	Cast & Forged	crack with 1/8" separation across length of one cast shoe, no damage to second cast shoe or forged shoe	10953 -3	12,13, 14
3 lb C-4 at 3"	Cast & Forged	both cast shoes heavily cracked and separated from pin, forged shoes undamaged	10953 -4	15,16, 17

* the round hit the edge of the shoe, above its aim point, and went between the track block and the track pin.

5.0 Discussion of Work

The .50 APM2 was fired at muzzle velocity, 2940 fps, and the .30 APM2 was fired at muzzle velocity, 2760 fps. 20mm FSP rounds were fired at 2340 fps. Rounds were aimed at the pin bushing because of the criticality of the bushing in holding the track together. Also, there were a limited number of tracks available and some had been damaged in previous tests at CTC. The only undamaged location common to all tracks was the pin bushing area. Two rounds were fired at each track to provide a repeatable indication of behavior.

In cold temperature tests, the samples were chilled to -110°F in dry ice. Then they were removed and the rate of warming was observed. When the temperature rose to -55°F, the impact chamber door was closed and the round was loaded and fired. During this time, the temperature rose to the specified temperature of -40°F. Temperatures were recorded with a portable surface reading thermometer.

The blast test setups are shown in Figures 7,9,12 & 15. A ball of C-4 explosive was suspended above two linked track shoes set on a bed of sand. This test subjected both shoes to an equivalent amount of blast to provide a fair means of comparing the shoes. It did not simulate an actual mine threat. To simulate a mine, the explosive would have been buried under the shoes with a fixture simulating the suspension and structure of a vehicle placed over the shoes. This would have been costly.

Preliminary tests were conducted on linked forged shoes to determine the amount and height of explosive to cause track shoe damage. Forged shoes were used because of the limited availability of cast shoes. The first test with a 3 lb ball of C-4 at 6" caused no damage to the shoes, links or pins. It did shift the rubber track pads. The second test was at 6 lb at 3". It broke two of the track links and cracked the third, but caused no damage to the forged shoes. These tests provided a range of severity between no damage and a track failure.

The linked forged and cast shoes were tested with 3 lb of C-4 at 3". In the first test, one of the cast shoes sustained a crack with 1/8" separation running along the length of the pin bushing. There was no damage to the other cast shoe, the forged shoes, links or pins. This test was repeated for verification. It resulted in heavy cracking and separation of both cast shoes from the pins. There was no damage to the forged shoes, links or pins.

KE round firing was conducted at FMC's Terminal Ballistics Lab from November 19 to 21, 1991. Blast tests were conducted at FMC's Ballistic Technology Lab in Hollister on December 3, 1991. Testing and test results are recorded on video tape. Additional mechanical tests were conducted at FMC's CTC. Test plan 10953 for blast testing is attached.

6.0 Recommendations for Future Testing

The impacted cast shoes could be tested to determine if they would break on the vehicle.

Cast shoes could be tested at lower velocities to determine at what velocity cracks start to occur. Forged shoes could be tested at higher FSP velocities to determine the onset of cracking.

KE tests could be conducted at different locations on the track.

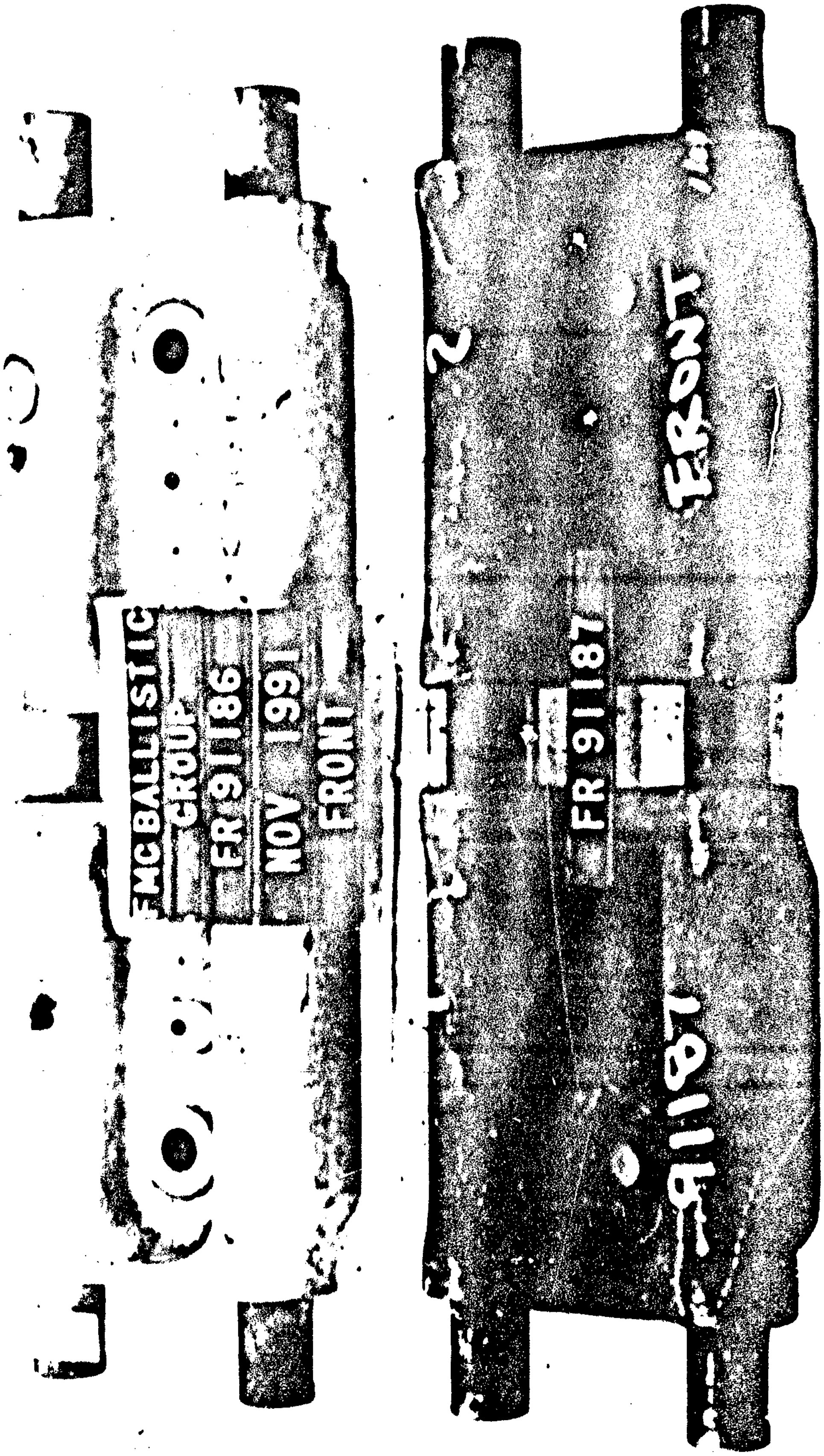

Figure 1. Cast and Forged shoes tested with .30 APM2 at 60°F

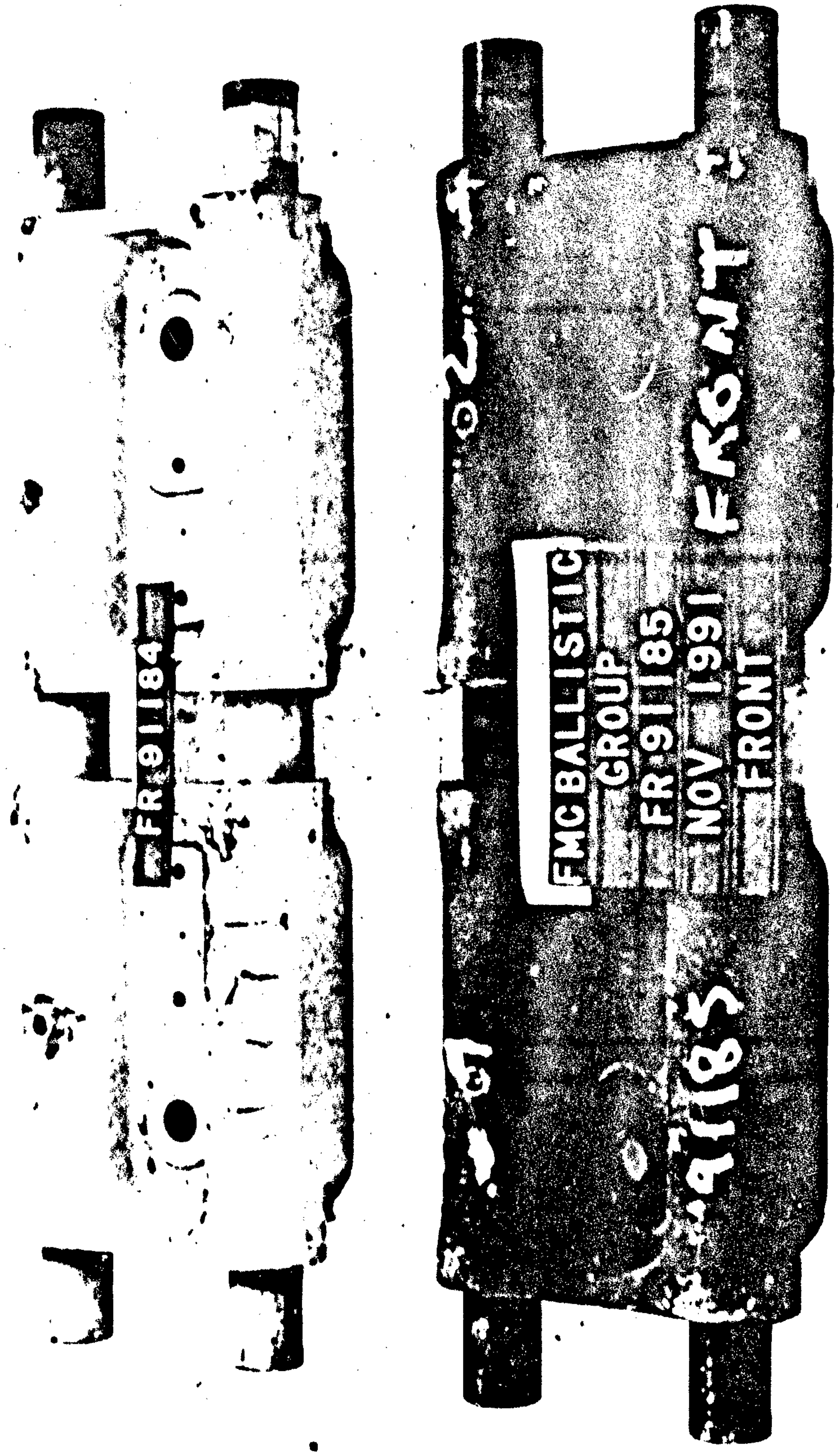

Figure 2. Cast and Forged shoes tested with .30 APM2 at $-40^{O}F$

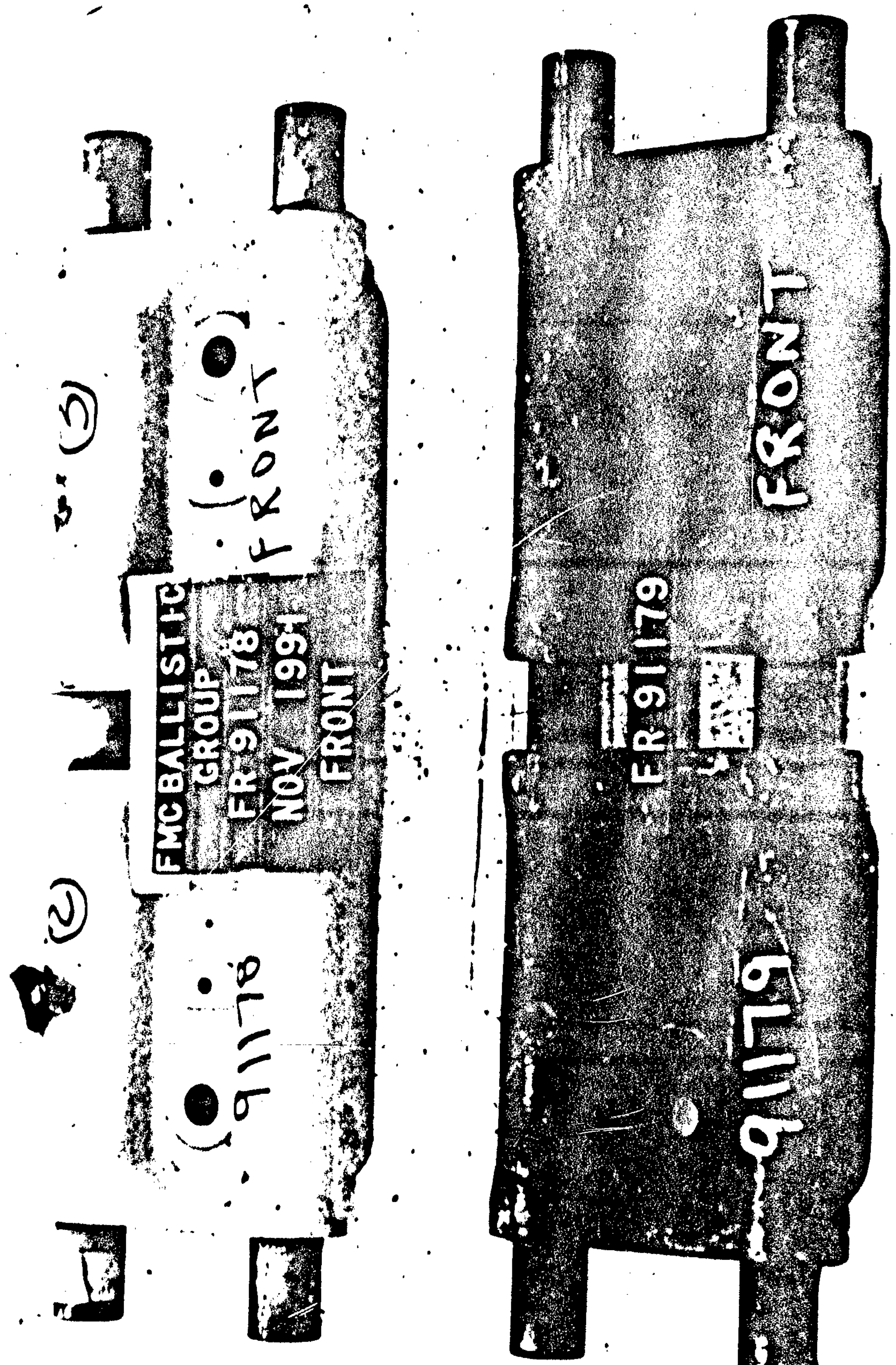

Figure 3. Cast and Forged shoes tested with .50 APM2 at 53°F

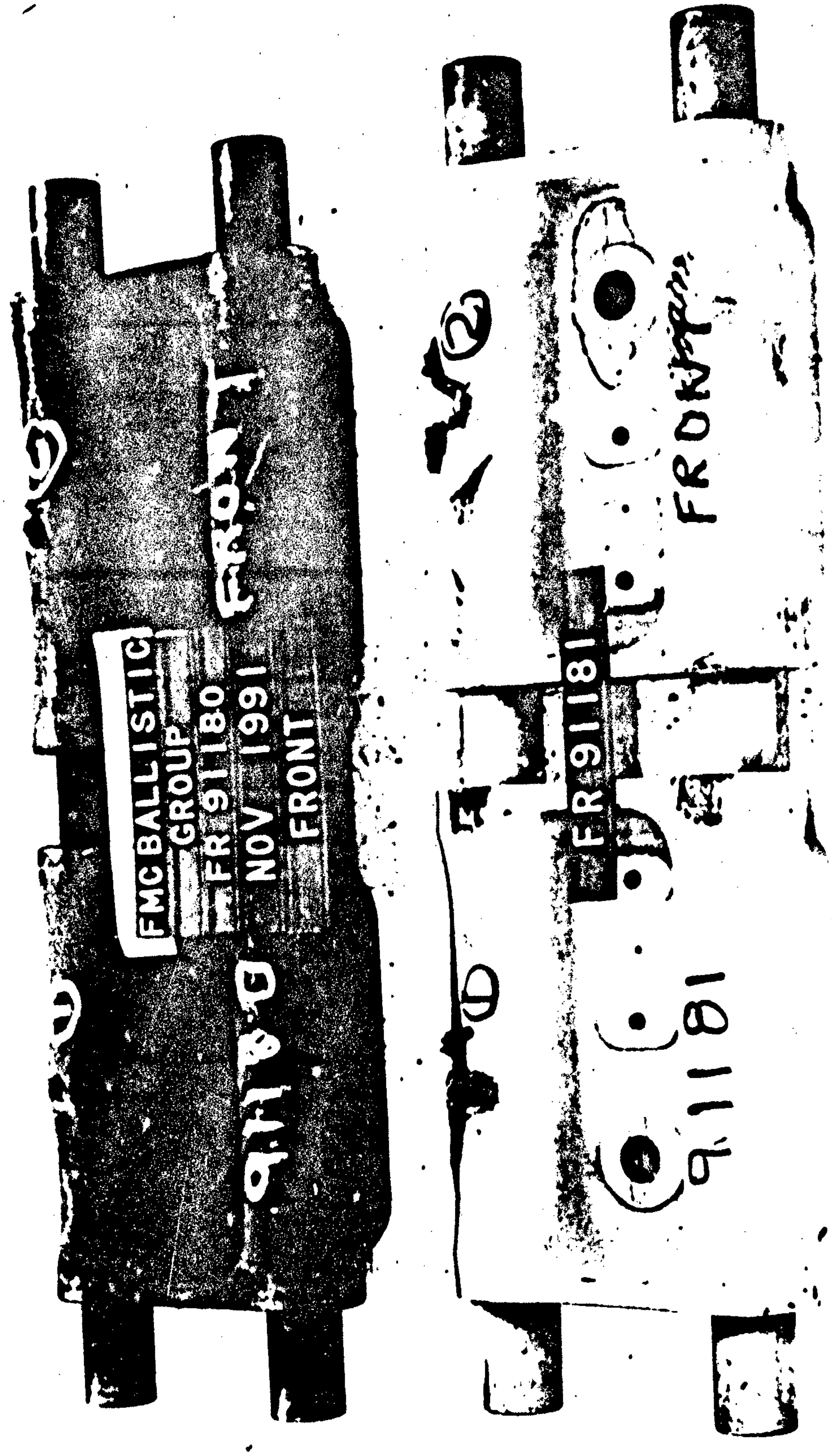

Figure 4. Cast and Forged shoes tested with .50 APM2 at $-40^{o}F$

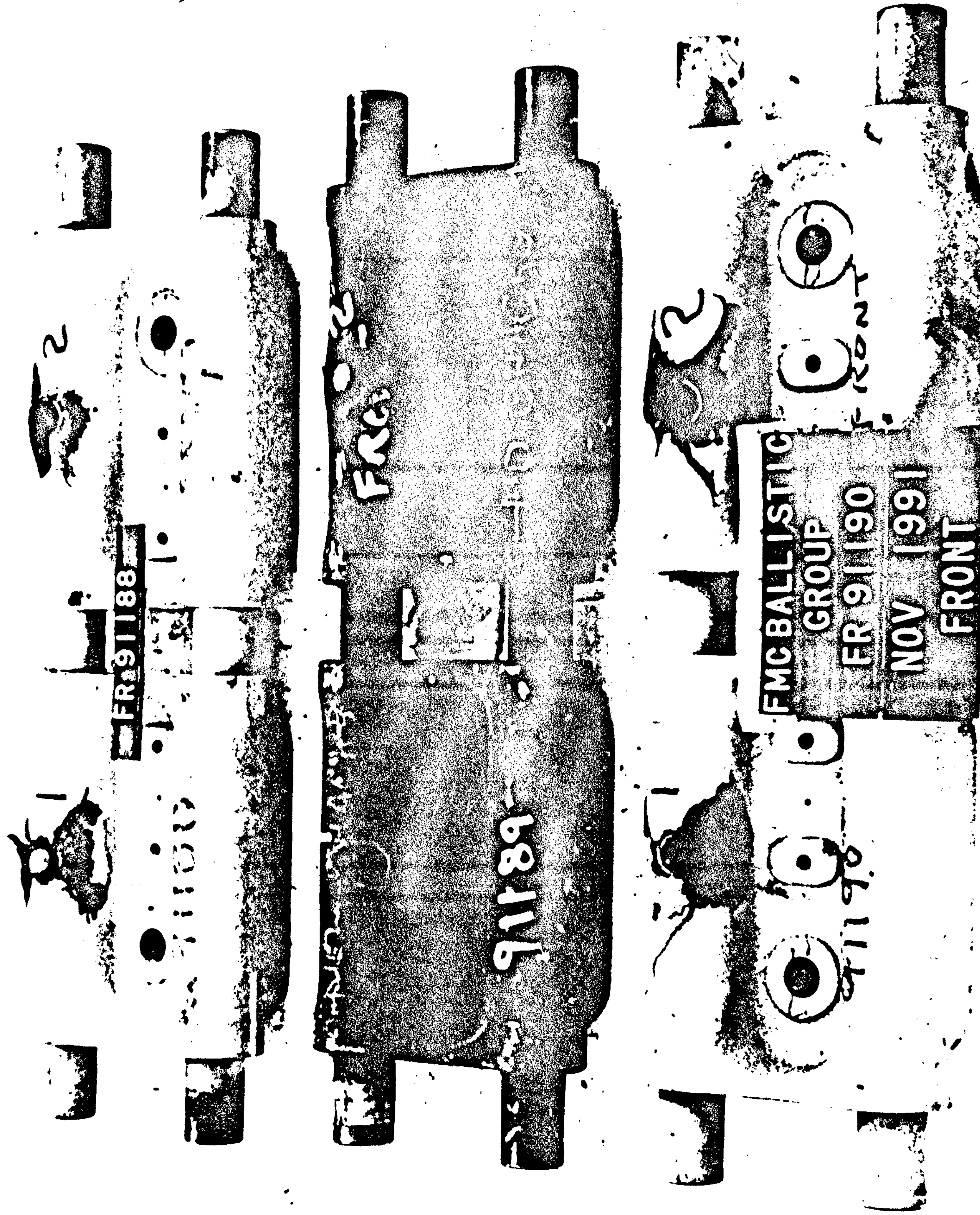

Figure 5. Cast and Forged shoes tested with 20mm FSP at 63°F

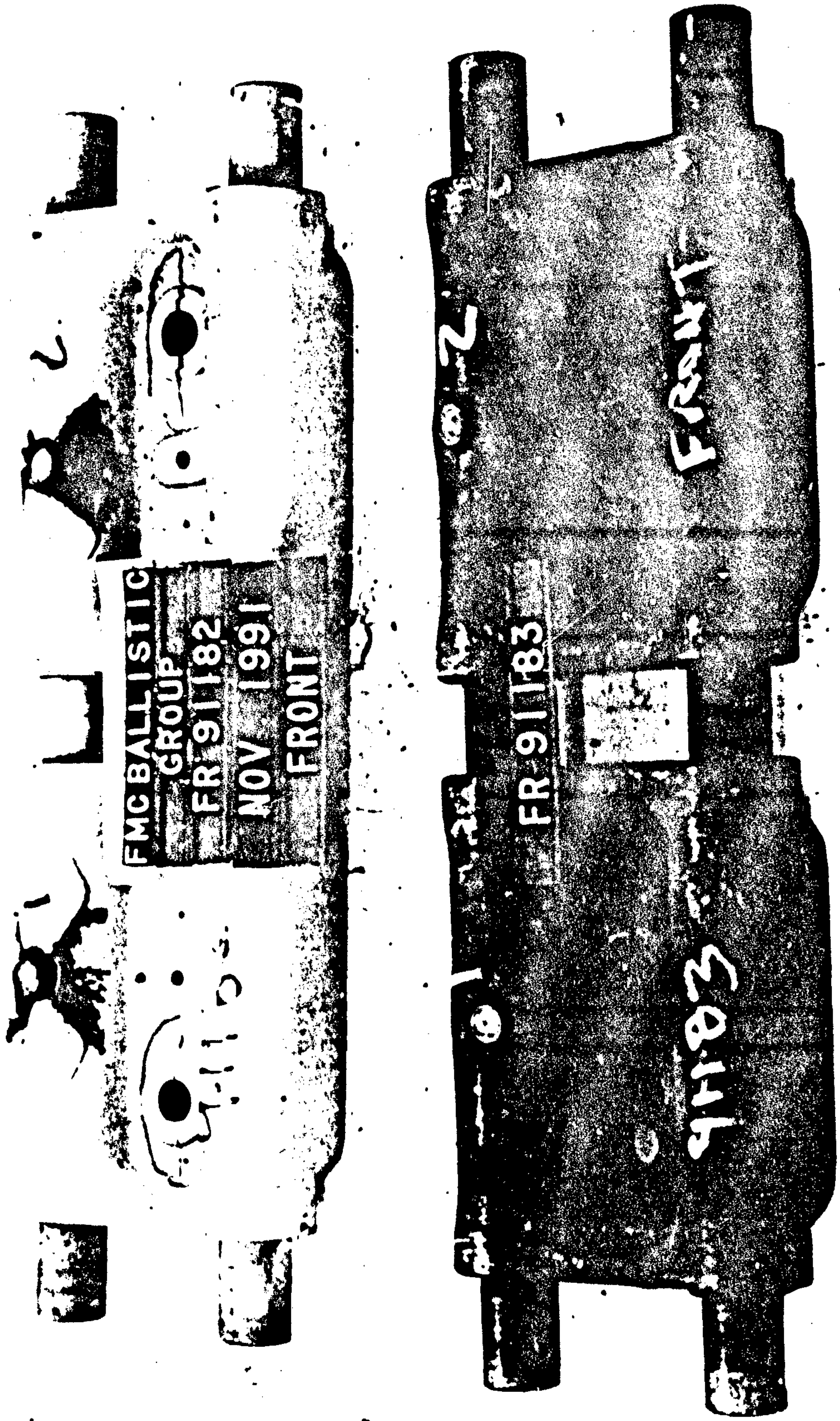

Figure 6. Cast and Forged shoes tested with 20mm FSP at $-40^{o}F$

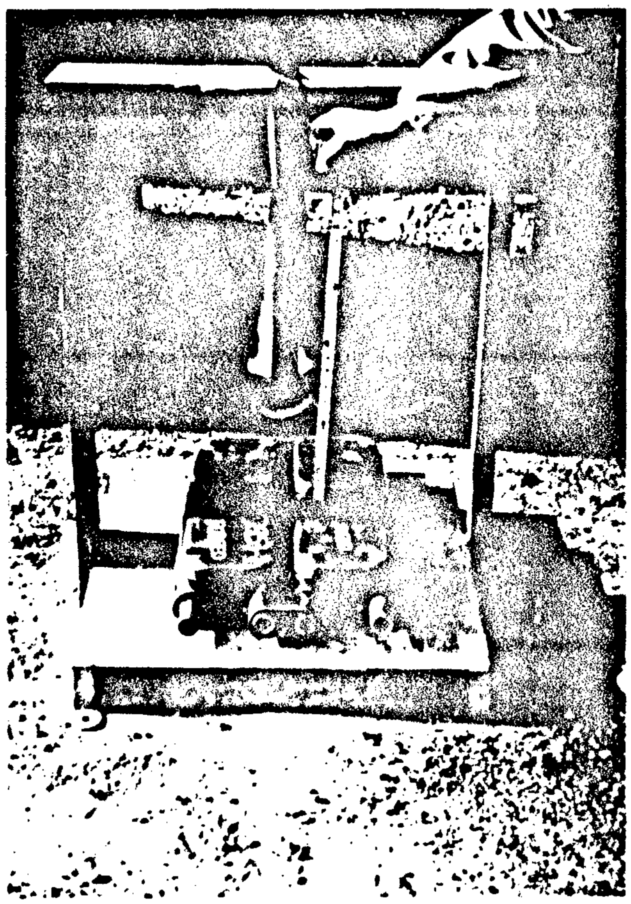

Figure 7. Forged - Forged Shoe Test To Determine Blast Height and Weight (3lb C-4 at 6")

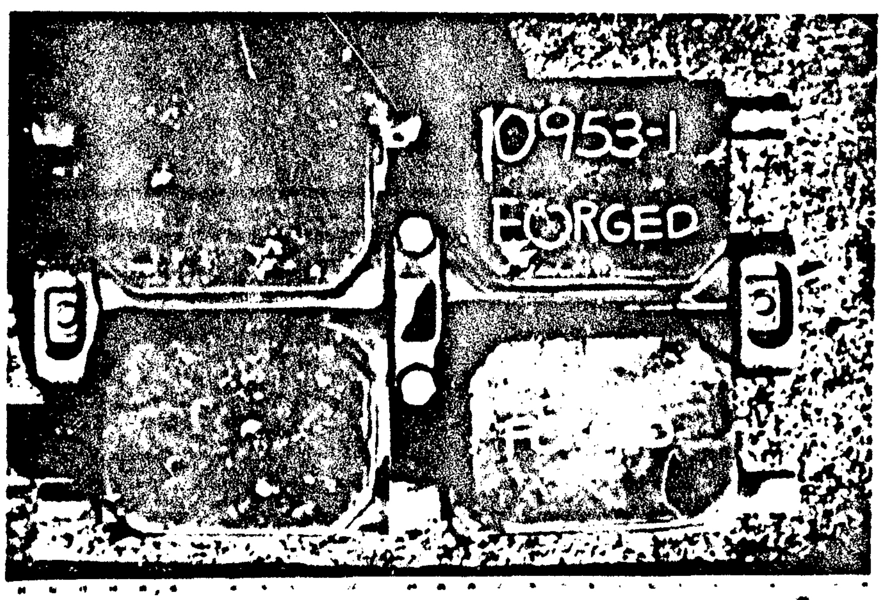

Figure 8. Forged - Forged Shoe Test, No Damage

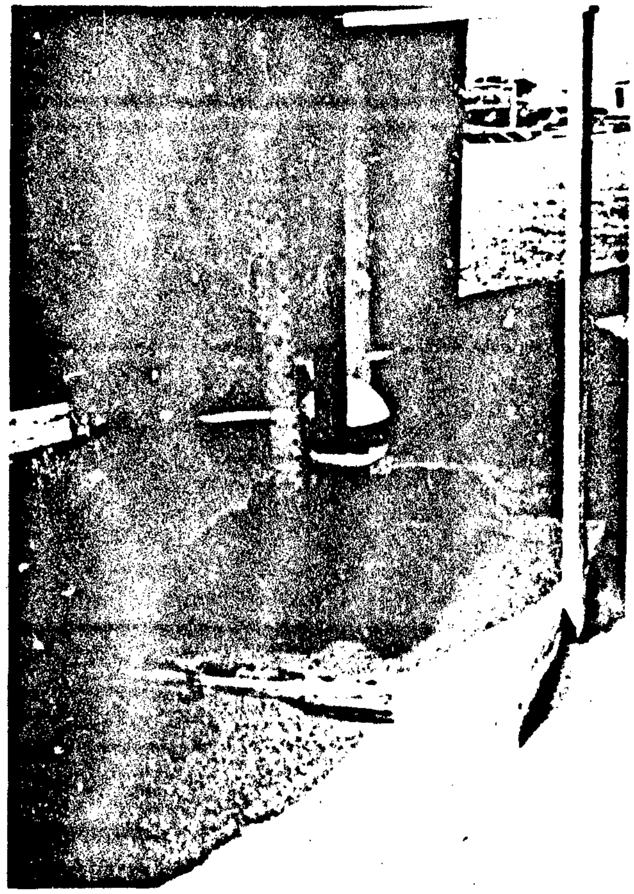

Figure 9. Forged - Forged Shoe Test To Determine Blast Height and Weight (6lb C-4 at 3")

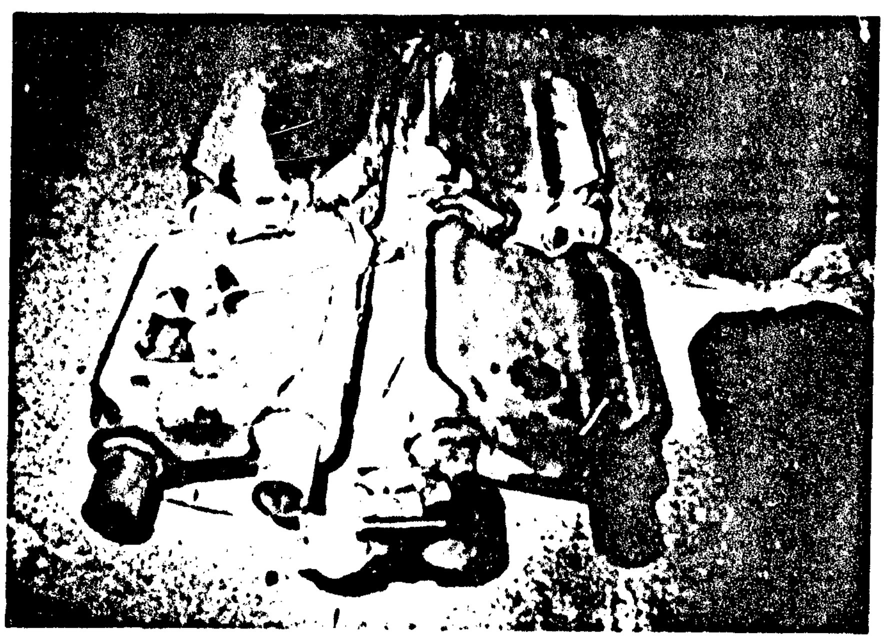

Figure 10. Forged - Forged Shoe Test, Broke Track Links

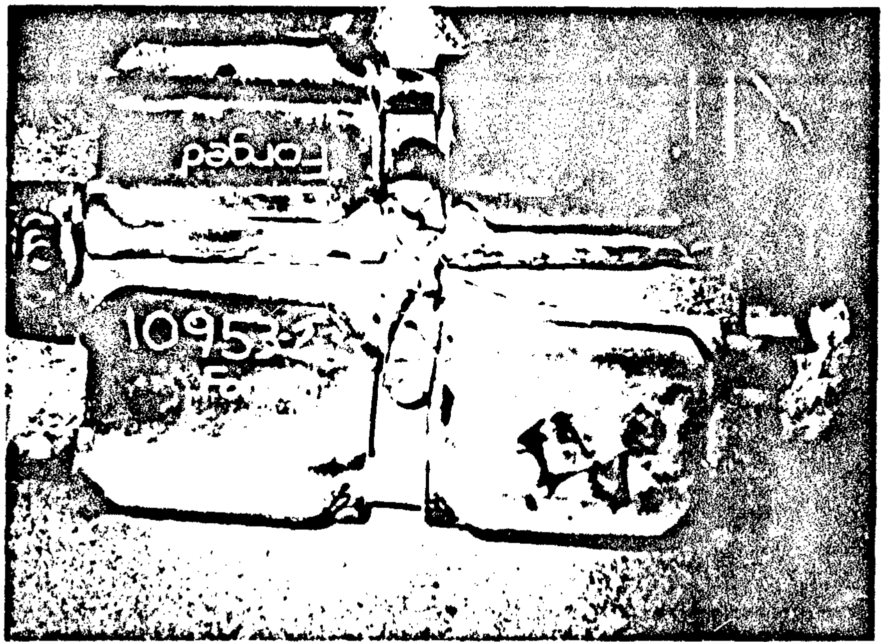

Figure 11. Forged - Forged Shoe Test, Broke Track Links

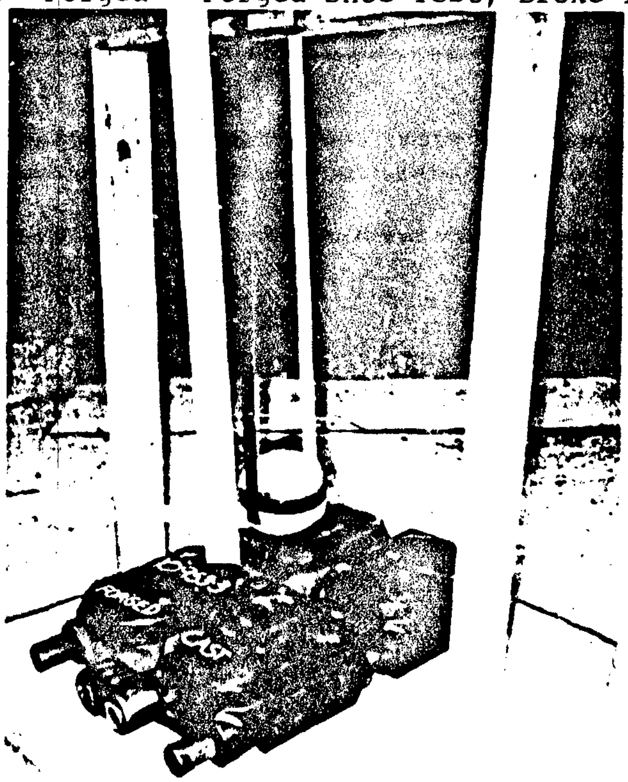

Figure 12. Cast - Forged Comparison Test (3lb C-4, 3")

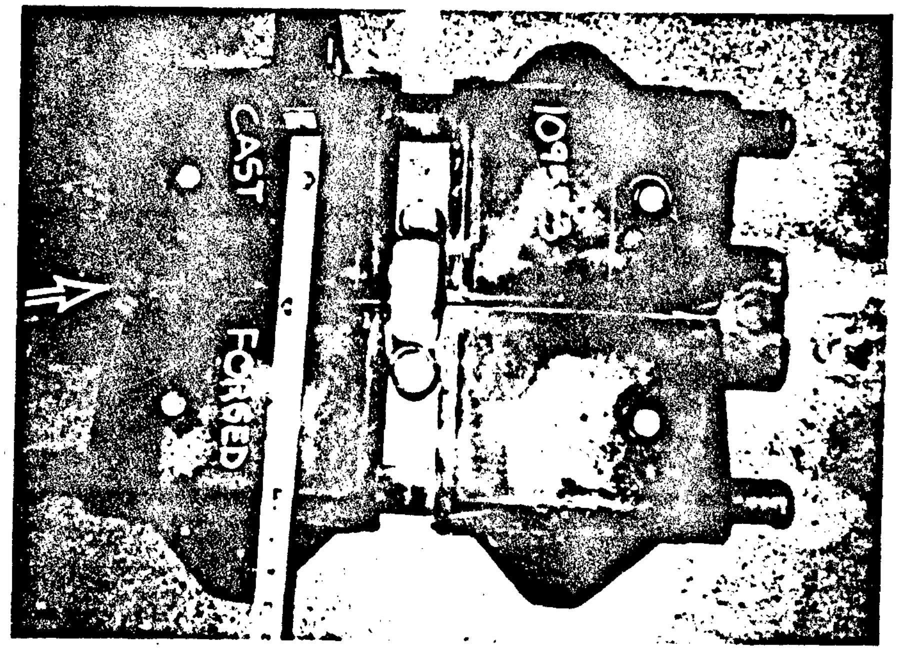

Figure 13. Cast - Forged Shoe Test, Note Crack at Arrow

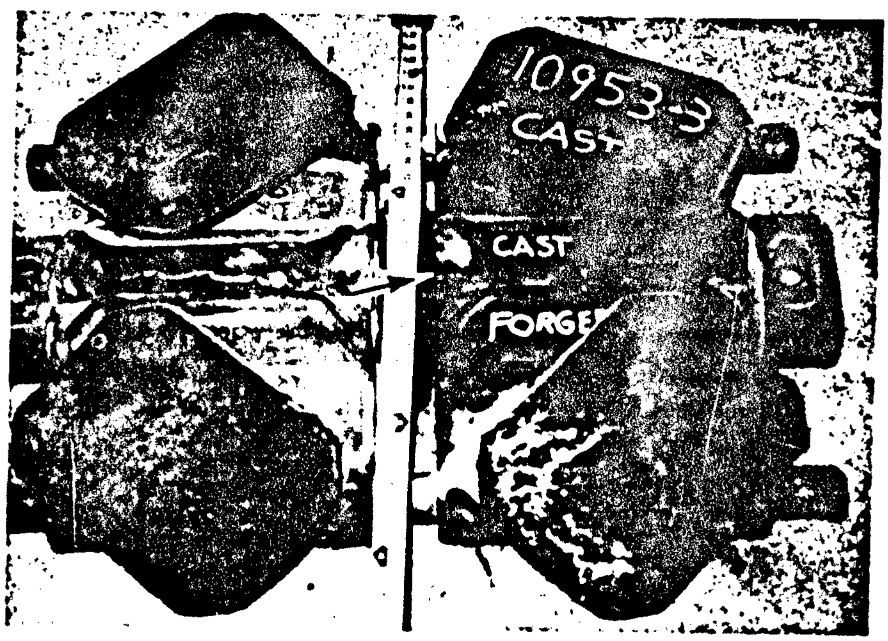

Figure 14. Cast - Forged Shoe Test, Note Crack at Arrow

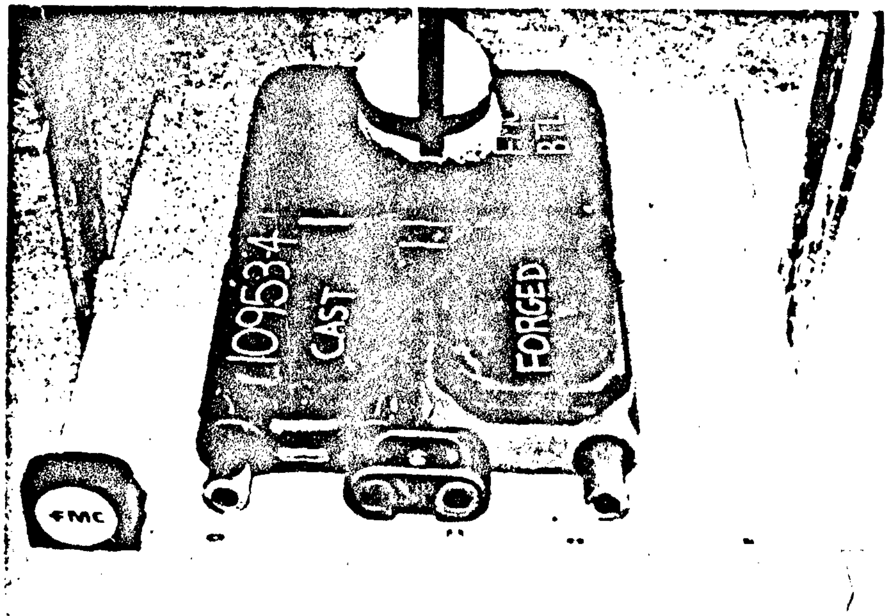

Figure 15. Cast - Forged Shoe Comparison Test (3lb C-4, 3")

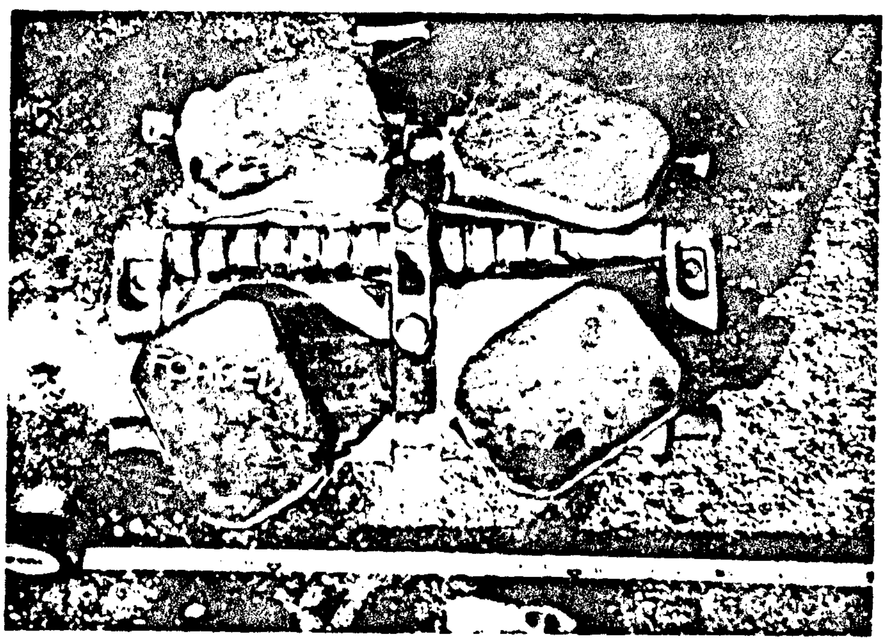

Figure 16. Cast - Forged Comparison Test Results

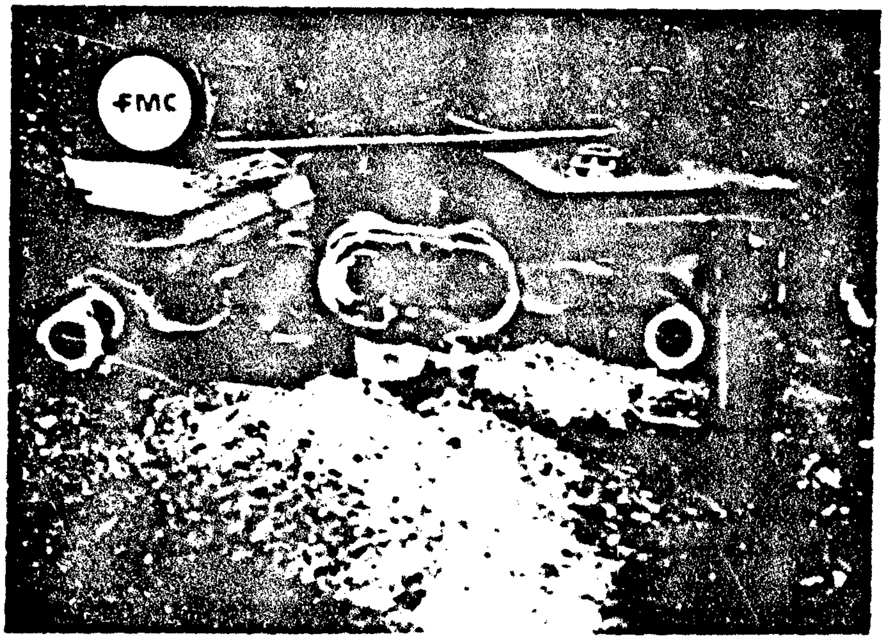

Figure 17. Cast - Forged Comparison Test Results

PAULO

PAULO PRODUCTS COMPANY

HEAT TREATERS AND FINISHERS OF METALS

Appendix IV

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ST. LOUIS,
MISSOURI 63110

ST LOUIS
BIRMINGHAM
CLEVELAND
KANSAS CITY
MEMPHIS
MURFREESBORO
NASHVILLE

314/647-7500
FAX 314/647-7518

April 26, 1991

Mr. Lyle Barnard
FMC Corporation
2101 West Tenth Street
Anniston, Alabama 36202

REFERENCE: 2-130

SUBJECT:

A set of twenty T-158 track shoes and seven Y-blocks were submitted to Paulo in Kansas City for experimental austempering operations on Shop Order 106970. These components were to be processed per ASTM A897-90, grade 175/125/4.

This work is a direct extension of previous work on the same subject Paulo shop order 106970, (please reference report MAR 2-128). The previous report detailed processing sequences and results of a single Y-block with an aim BHN of 375-425. A transformation temperature of 575 F was used, which resulted in a surface hardness of BHN 415. Unfortunately, two primary problems were noted with this experiment; (1) intermediate products in the center of the coupon and (2) the possibility of martensite within the core.

From discussions with Mr. Gary Hudson at FMC, it was decided that the Y-block coupon section thickness was not representative to the actual cross section of the track shoes. Additionally, the target hardness was to be decreased to BHN 350-375 F, and the transformation time to be extended an additional 1/4 hour to help eliminate martensite formation.

PROCEDURES AND OBSERVATIONS:

All test coupons were submitted to a machine shop, and longitudinally split to decrease the cross sectional area for better correlation to the track shoes.

The track shoes, and machined Y-blocks were prepared for austempering treatments. The quench rate of the transformation bath was maximized, and a transformation temperature of 625 F was chosen for a period of 1-3/4 hours. The processing sequence is displayed in Table I.

One machined Y-block was submitted to Paulo in St. Louis for metallurgical analysis. The surface of the block was prepared for hardness testing per ASTM E10. The surface hardness was determined to be BHN 363.

The Y-block was transversely sectioned to reveal the complete cross section. The cross section was prepared for hardness testing. The entire cross section exhibited a hardness of BHN 363, which was identical to the surface hardness.

The full cross section of the block was prepared for metallography per ASTM E3. The entire core structure consisted of a slightly segregated retained austenite and bainitic ferrite. No significant or detectable anomalies were noted in the final structure. Figure 1 presents a typical micrograph.

CONCLUSIONS:

The process development of the experimental austempering operations appears to have been successful at eliminating detrimental microstructure constituents, and produce desired hardness levels. Mechanical tests will be performed on the experimental product. Results of these tests may necessitate process modifications in order to provide desired mechanical properties.

ATTACHMENTS:

Table I: Heat Treatment Parameters
Figure 1: Typical Microstructure

Sincerely

Paulo Products Company

Rob Simons

Rob Simons
Quality and Metallurgical Engineering

Table I
Heat Treatment Parameters

group	austen temp	austen time	trans temp	trans time
Production	1650	1-1/4 hr	625	1-3/4 hr

Magnification: 400x
Etch: 3% Nital

Figure 1
Typical Microstructure

APPENDIX V

The following is written directly from pages 3-5 of TECOM Test Report #1-VC-087-130-004 entitled, "Final Letter Report, Product Improvement Test of T-130E1 Track and Suspension Components", dated 6 April, 1977. The objective of the test was to determine the durability of track components produced by the isothermal heat treatment (austempering) of ductile iron at low temperatures. Paragraphs 5a and 5g are reproduced, along with Table 3 - Component Failure Condi ons.

5. SUMMARY OF RESULTS

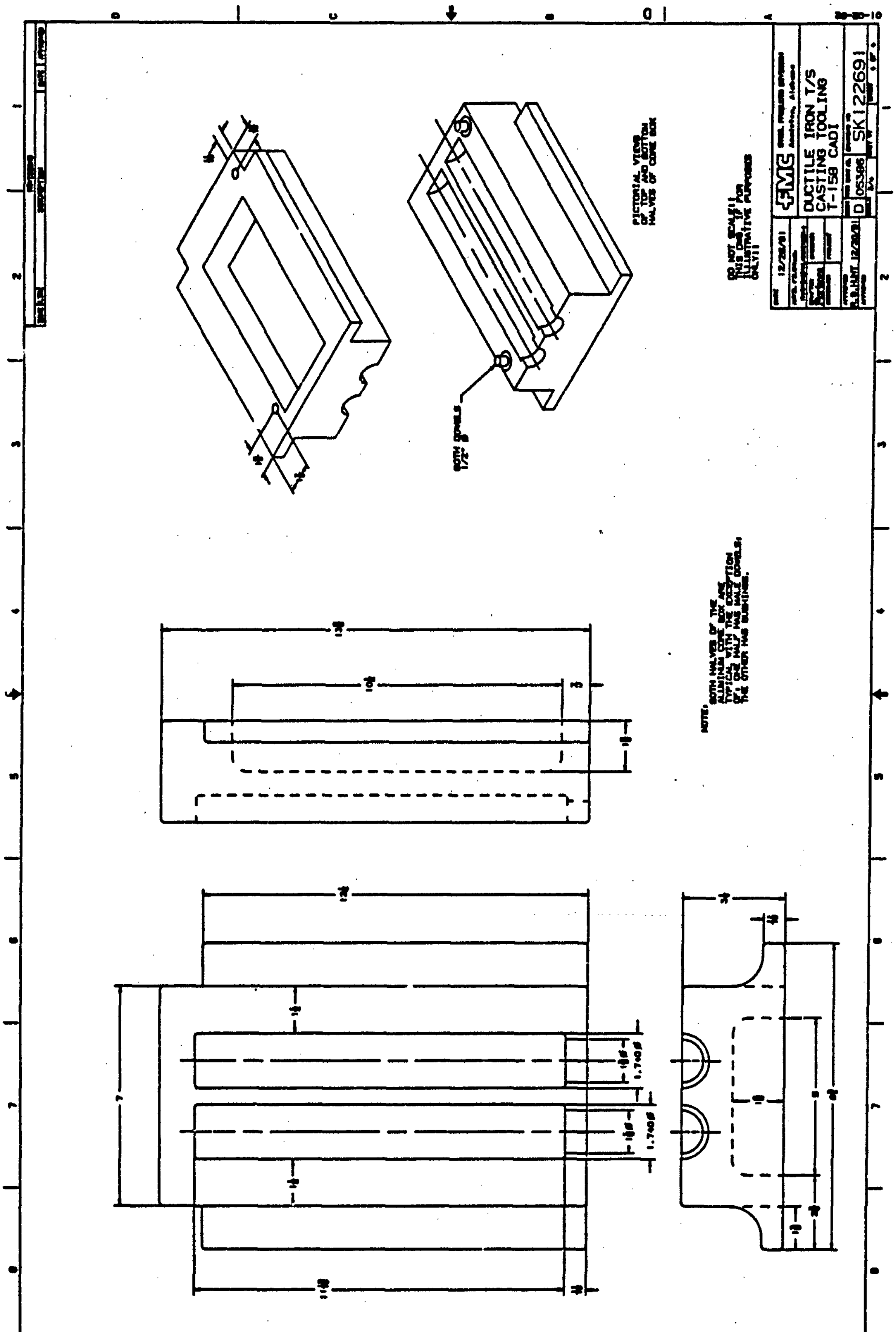
a. The T-130E1 test components failed to satisfy the overall test objectives in that they demonstrated a significantly reduced durability when compared to the standard steel components.

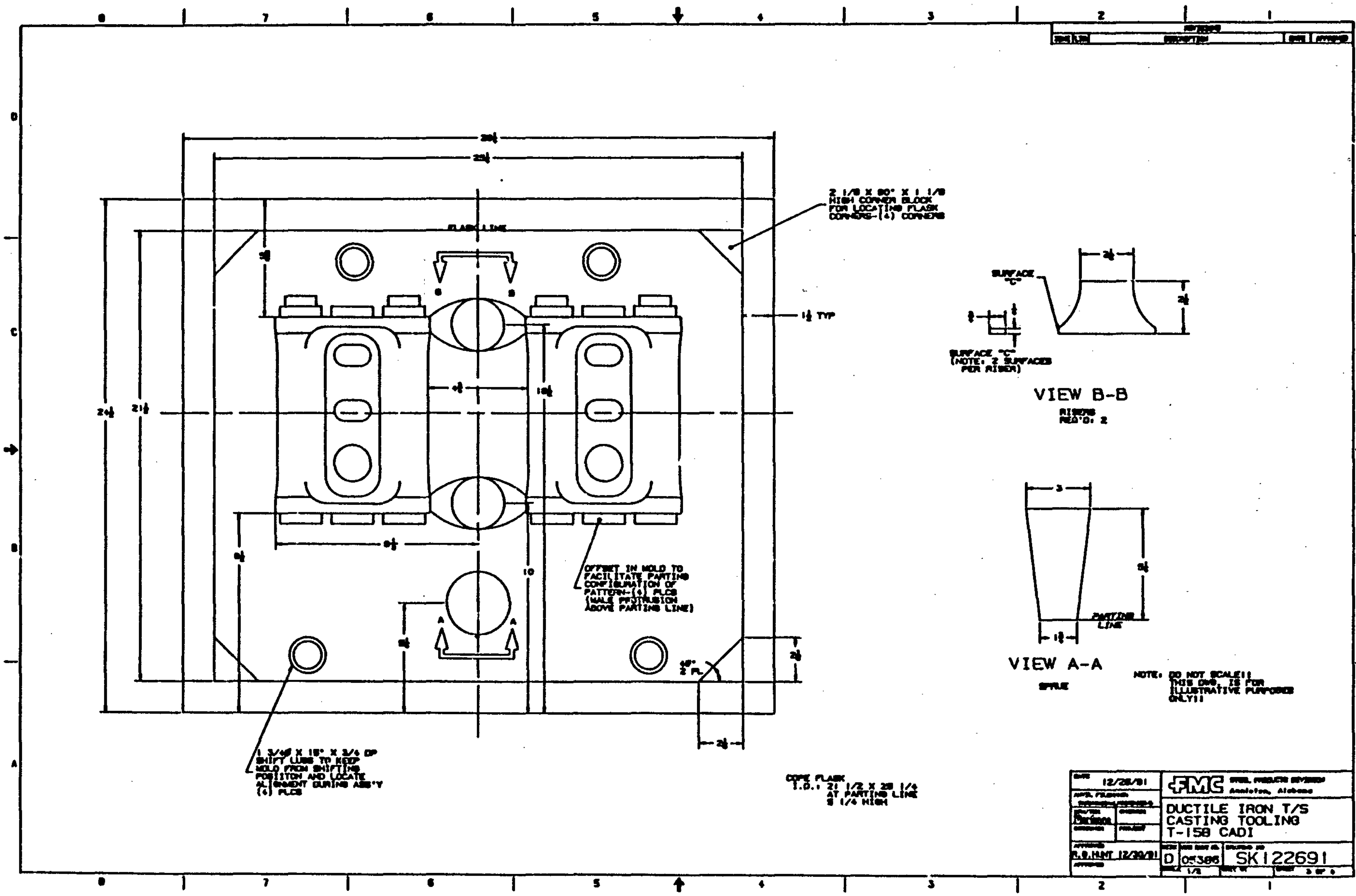
g. Of the 64 track blocks and three sprockets received and tested, 22 track blocks were broken along with one sprocket, number T1 (see photos 1 through 6 for examples of failures). The distance traveled and temperature ranges last encountered prior to discovery

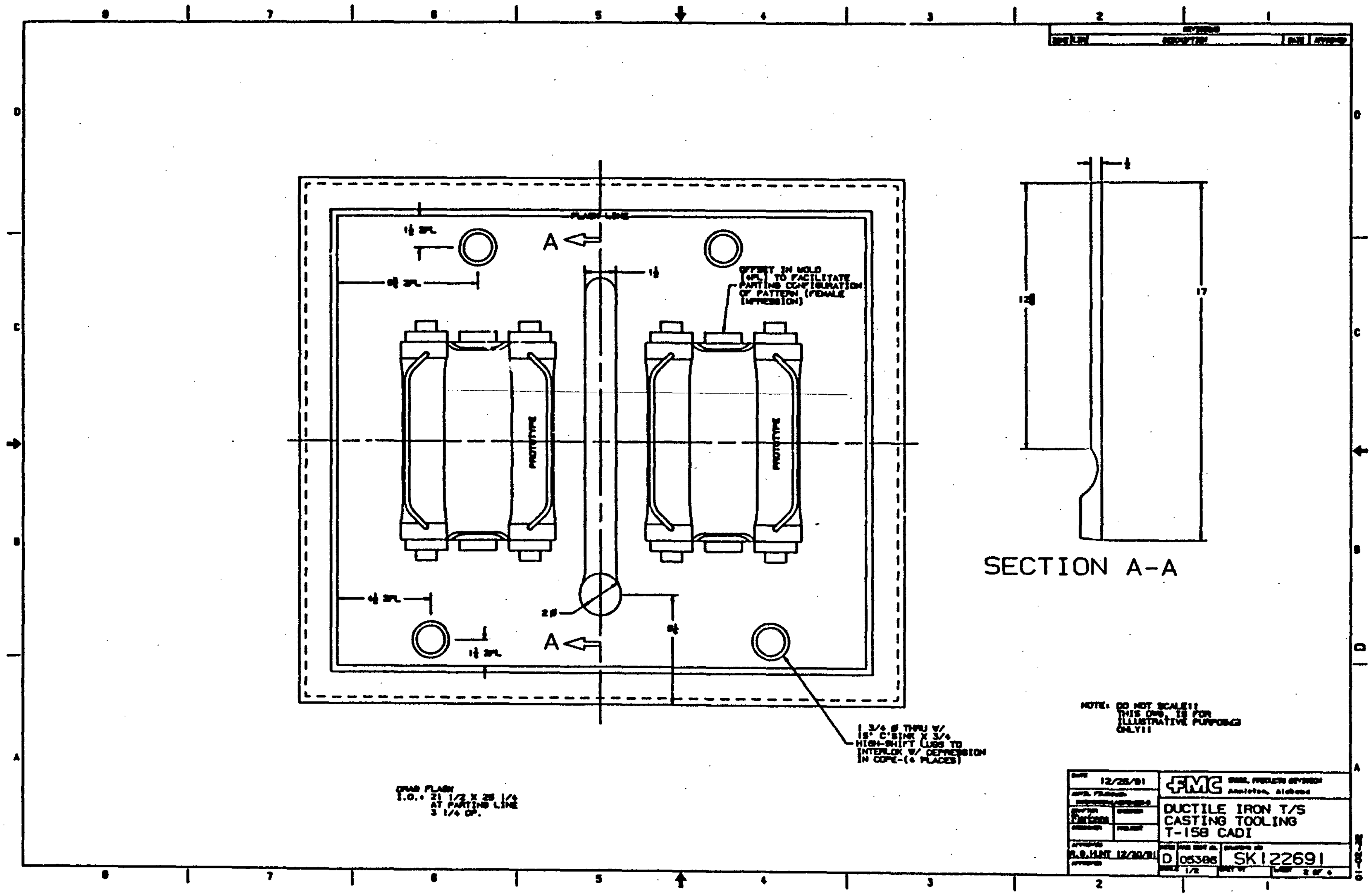
of the failures are shown in Table 3. There were no failures of the standard stock steel components. The test components experienced 23 chargeable durability failures in 1335 kilometers. This demonstrates a mean kilometer between failure (MKBF) of 58 kilometers. CRTC received only one extra test track block which was used to replace the first failed block. The remaining 21 blocks that failed were replaced with new, standard stock steel blocks, none of which failed. As a result, the computed MKBF is probably higher than it would have been had the failed blocks been replaced with test track blocks. Since the standard components experienced no failures, the MKBF of the standard components cannot be computed directly. It should be noted that if one standard component failure had occurred, the MKBF would have been 1335 kilometers.

TABLE 3 - Component Failure Conditions

Block/Sprocket No.	Kilometers at Time of Breaking	Temperature Range
T3, T16, T27, T28, T37	573	$-32^{o}C$ to $-46^{o}C$
Sprocket T1	584	$-12^{o}C$ to $-32^{o}C$
T5, T60, T18, T19, T21, T23, T26	631	$-12^{o}C$ to $-32^{o}C$
T29, T31, T38, T48, T49, T50		
T57, T63	1,037	$-12^{o}C$ to $-32^{o}C$
T12, T40	1,335	$-12^{o}C$ to $-32^{o}C$


DUCTILE IRON T/S
CASTING TOOLING
T-158 CADI
SK122691
PICTORIAL VIEWS
OF TOP AND BOTTOM
HALVES OF CORE BOX
DO NOT SCALE!!
THIS DWG. IS FOR
ILLUSTRATIVE PURPOSES
ONLY!!
BOTH DOWELS
1.740 Ø
1.740 Ø


FLASK LINE
2 1/8 X 80° X 1 1/8 HIGH CORNER BLOCK FOR LOCATING FLASK CORNERS-(4) CORNERS
1½ TYP
OFFSET IN MOLD TO FACILITATE PARTING CONFIGURATION OF PATTERN-(4) PLCS (MALE PROTRUSION ABOVE PARTING LINE)
1 3/4Ø X 15° X 3/4 DP SHIFT LUGS TO KEEP MOLD FROM SHIFTING POSITION AND LOCATE ALIGNMENT DURING ASS'Y (4) PLCS
COPE FLASK I.D.: 21 1/2 X 28 1/4 AT PARTING LINE 8 1/4 HIGH
SURFACE "C"
SURFACE "C" (NOTE: 2 SURFACES PER RISER)
VIEW B-B
RISERS REQ'D: 2
PARTING LINE
VIEW A-A
SPRUE
NOTE: DO NOT SCALE!! THIS DWG. IS FOR ILLUSTRATIVE PURPOSES ONLY!!
12/28/91
FMC
DUCTILE IRON T/S
CASTING TOOLING
T-158 CADI
D 05386 SK122691


SECTION A-A
A
A
FLASH LINE
OFFSET IN MOLD (4PL) TO FACILITATE PARTING CONFIGURATION OF PATTERN (FEMALE IMPRESSION)
PROTOTYPE
PROTOTYPE
1 3/4 ⌀ THRU W/ 15° C'SINK X 3/4 HIGH-SHIFT LUGS TO INTERLOK W/ DEPRESSION IN COPE-(4 PLACES)
DRAG FLASK I.D.: 21 1/2 X 25 1/4 AT PARTING LINE 3 1/4 DP.
NOTE: DO NOT SCALE!! THIS DWG. IS FOR ILLUSTRATIVE PURPOSES ONLY!!
17
2⌀
12/28/91
FMC
DUCTILE IRON T/S
CASTING TOOLING
T-158 CADI
D
05386
SK122691
1/2

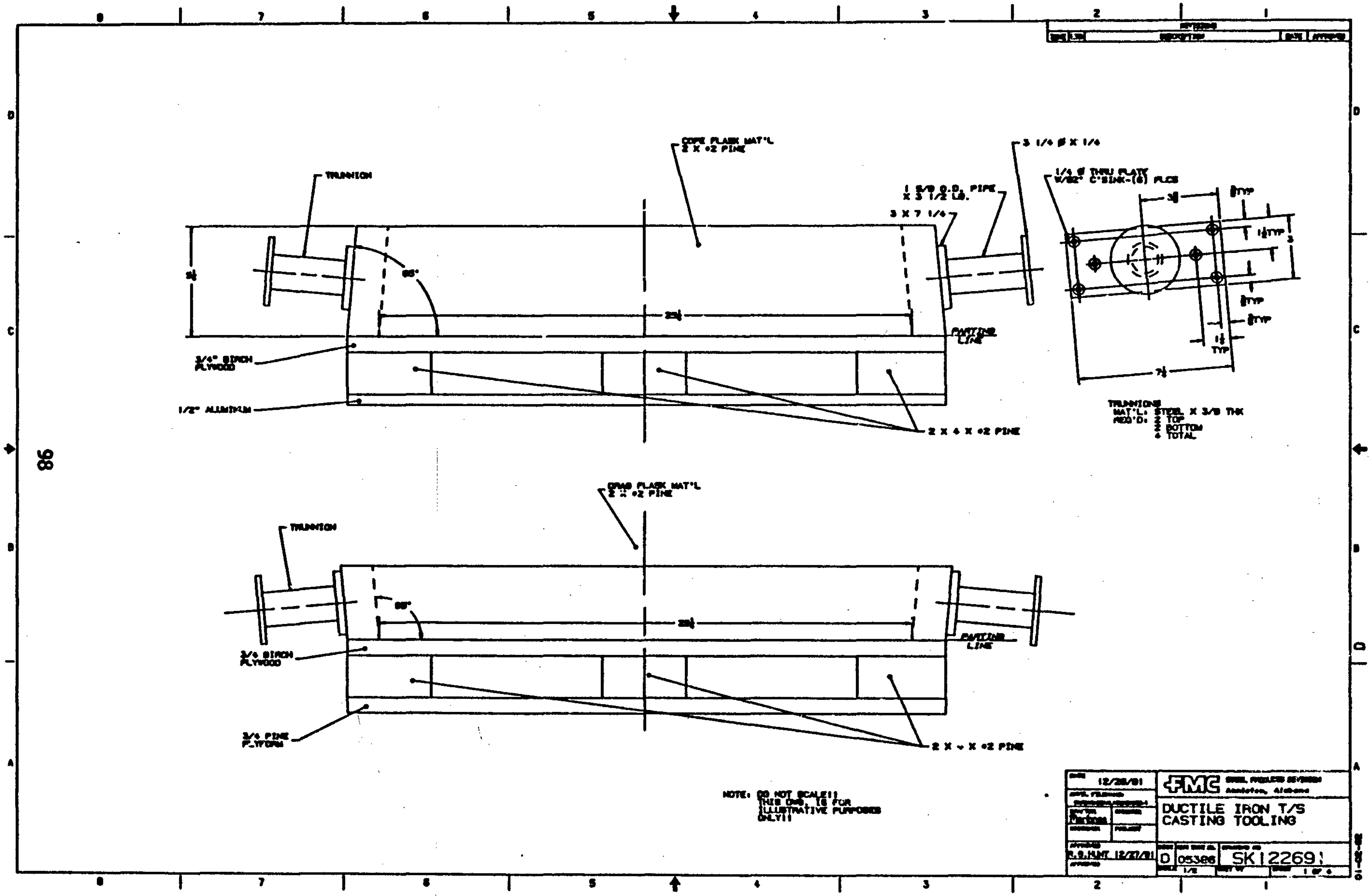
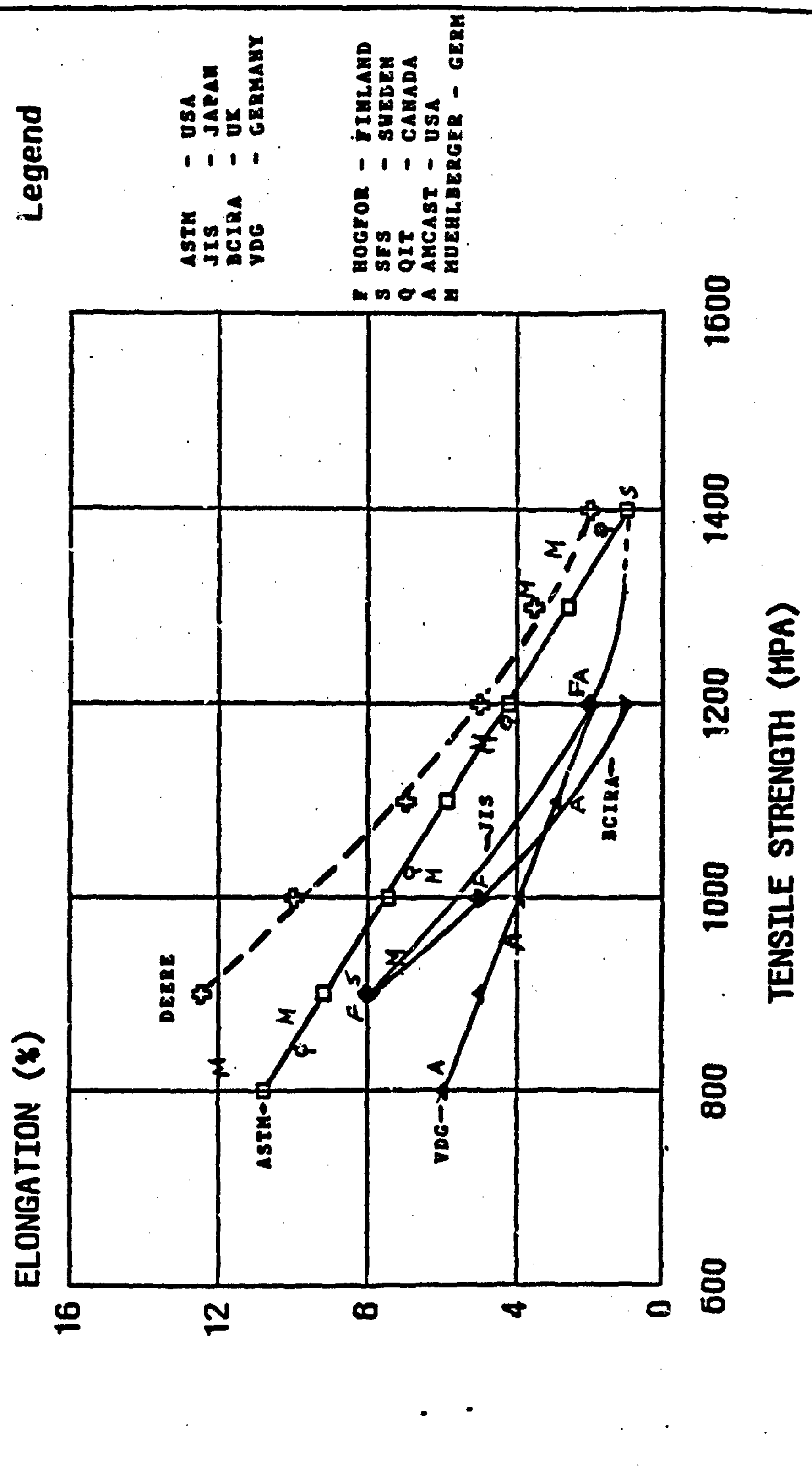

COPE FLASK MAT'L
2 X #2 PINE
TRUNNION
1 5/8 O.D. PIPE
X 3 1/2 LG.
3 X 7 1/4
3 1/4 Ø X 1/4
1/4 Ø THRU PLATE
W/82° C'SINK-(8) PLCS
3/4" BIRCH
PLYWOOD
1/2" ALUMINUM
PARTING
LINE
2 X 4 X #2 PINE
TRUNNIONS
MAT'L: STEEL X 3/8 THK
REQ'D: 2 TOP
2 BOTTOM
4 TOTAL
DRAG FLASK MAT'L
2 X #2 PINE
3/4 BIRCH
PLYWOOD
3/4 PINE
PLATFORM
NOTE: DO NOT SCALE!!
THIS DWG. IS FOR
ILLUSTRATIVE PURPOSES
ONLY!!
12/28/81
FMC
DUCTILE IRON T/S
CASTING TOOLING
R.S.HUNT 12/27/81
D 05386
SK12269

FIGURE 1. RELATIONSHIP OF MINIMUM SPECIFIED ELONGATIONS AND TENSILE STRENGTH FOR VARIOUS ADI SPECIFICATIONS



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